Mildly-relativistic collisionless shocks formed by magnetic piston

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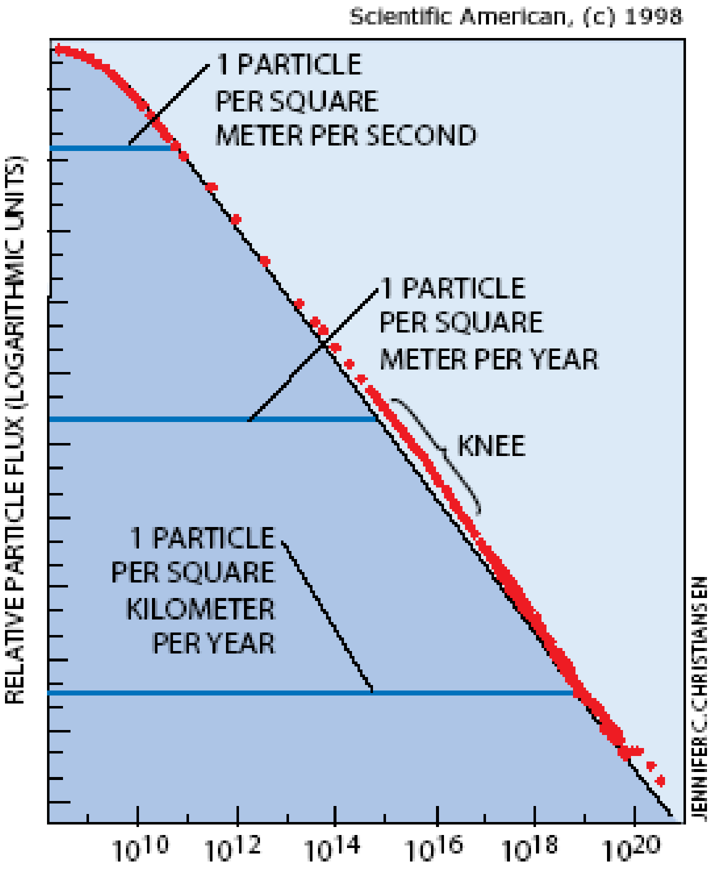
Why shocks are important in Astrophysics?

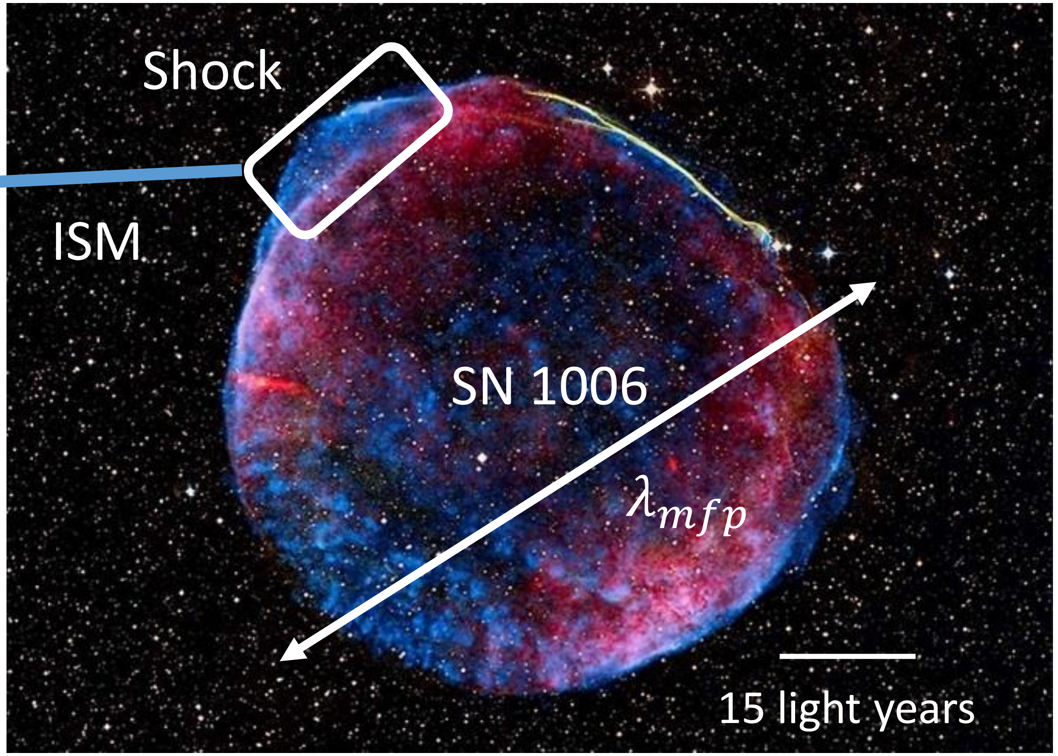
Cosmic ray spectrum



(J.W. Cronin et al. 1998)

Particles acceleration

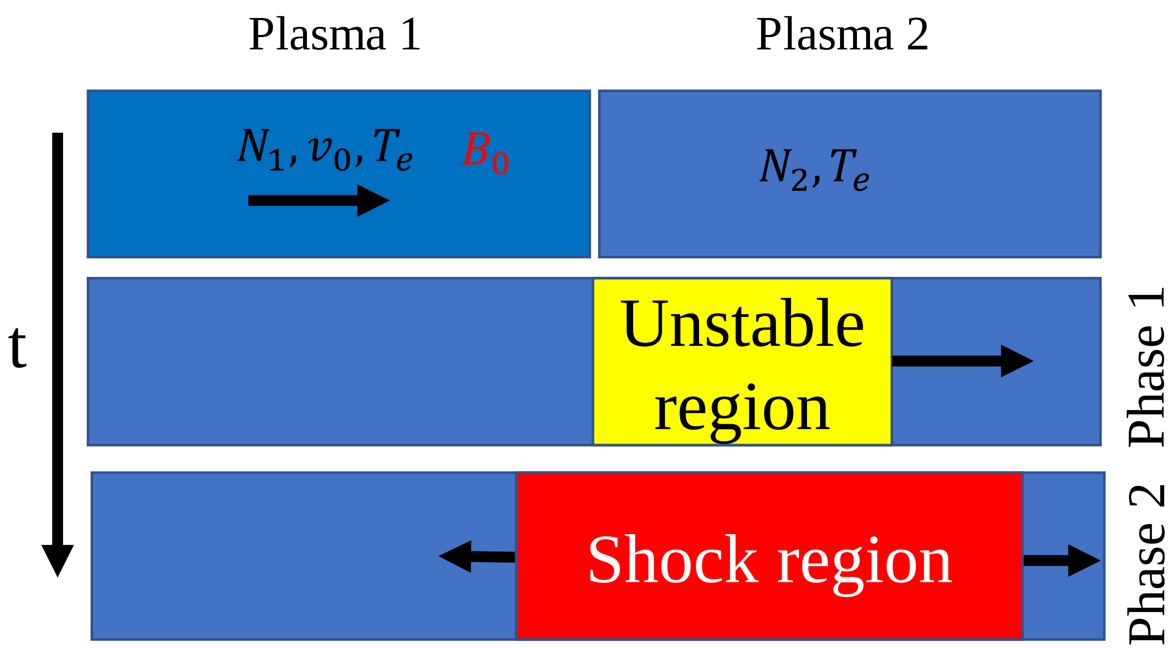
Credit: Chandra X-ray Observation



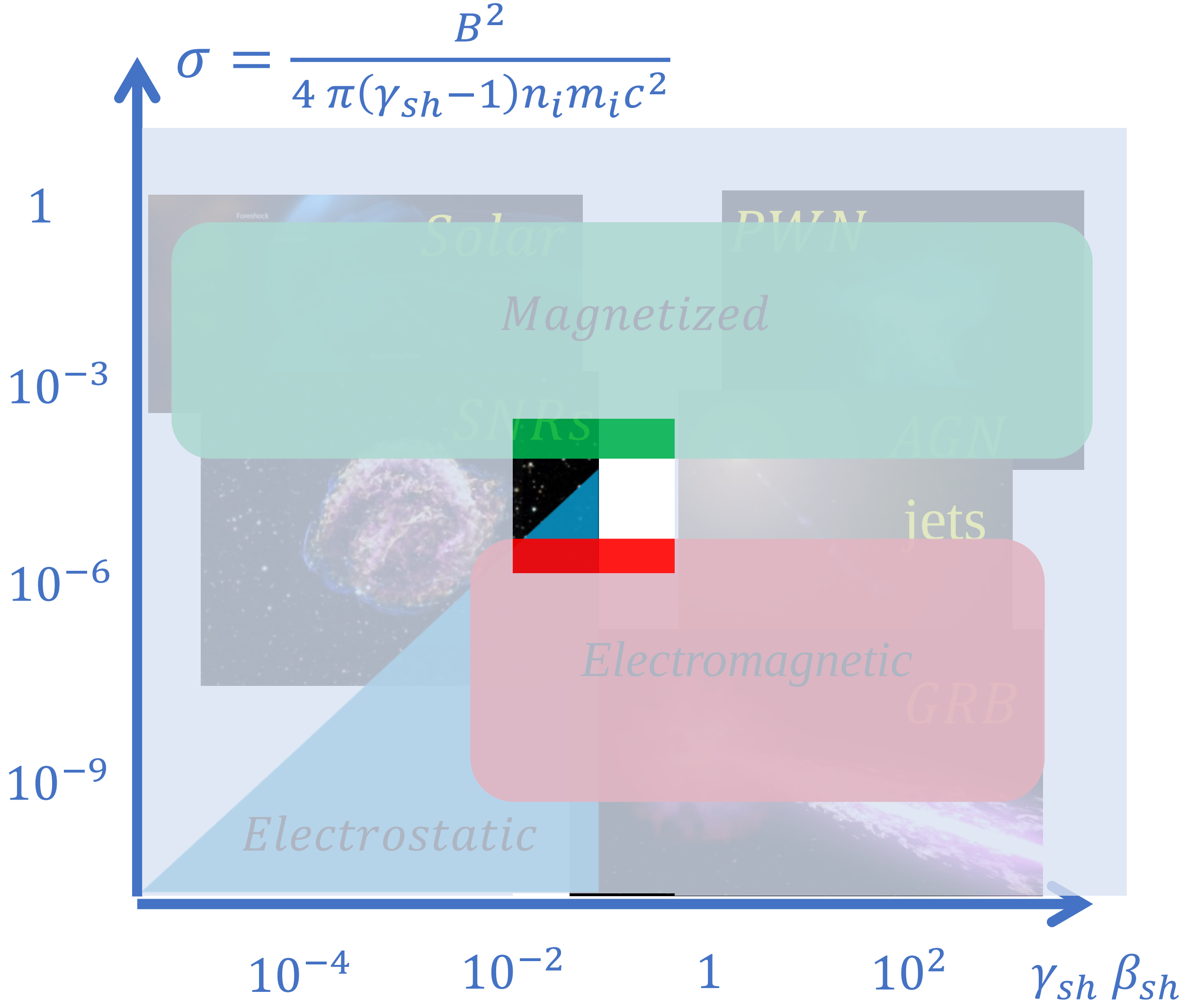
Most shocks are collisionless

Collisionless Astrophysical shocks?

Collisionless shock formation



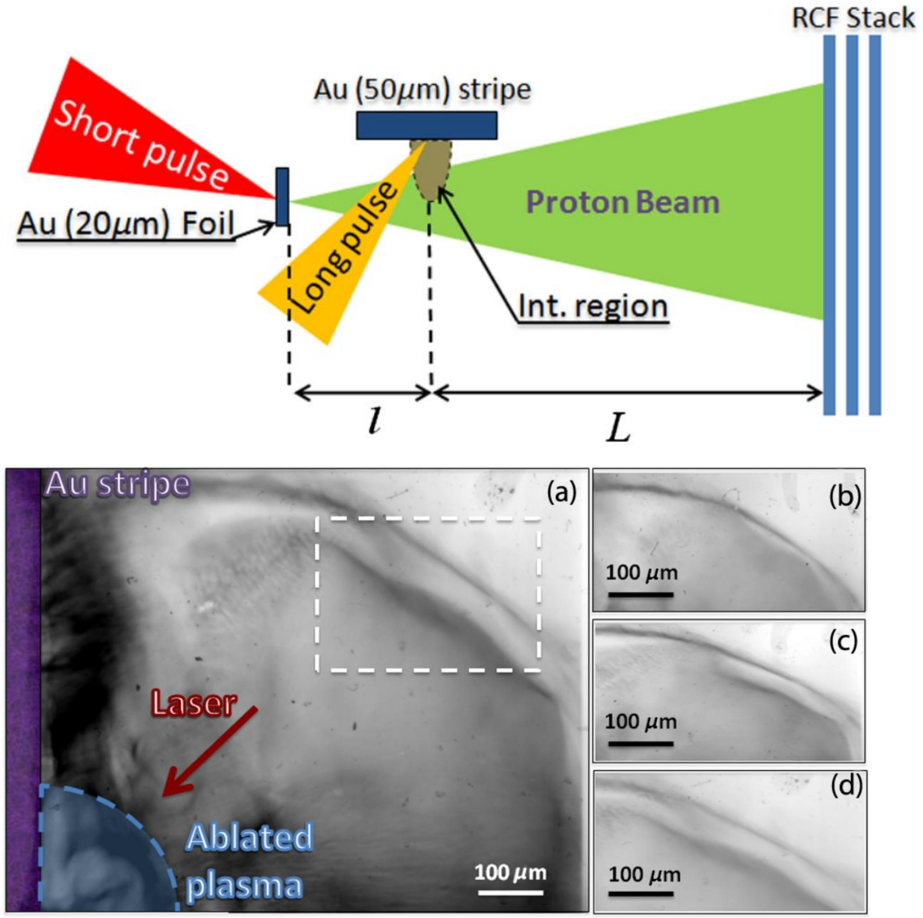
In the reference frame of Plasma 2



Adapted from A. Spitkovsky

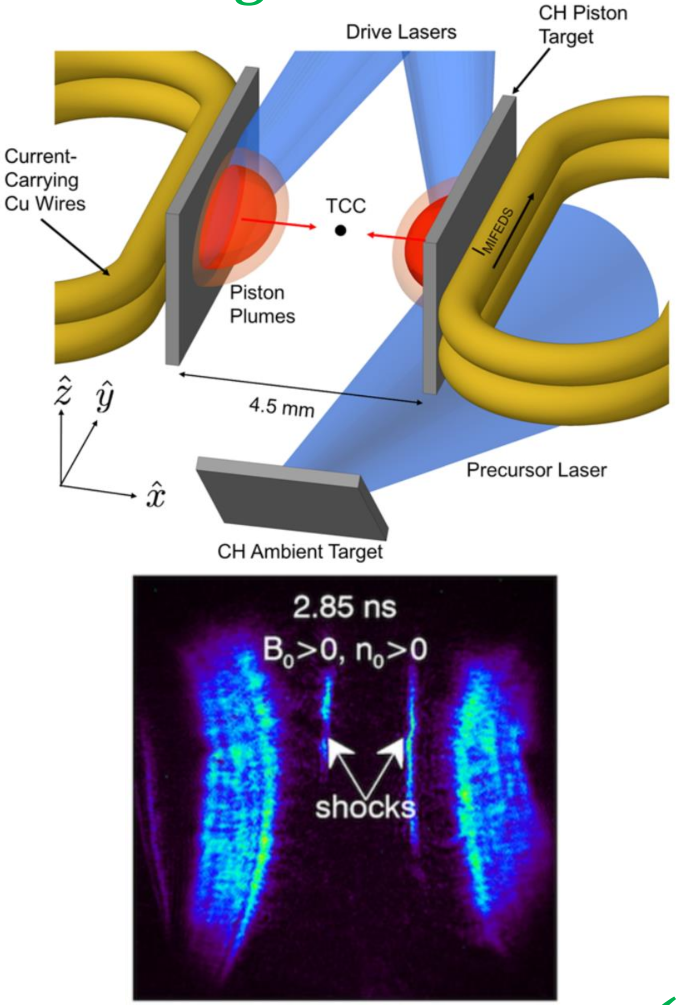
Overview of collisionless shocks in laboratory

Electrostatic



(Ahmed et al., 2013) ✓

Magnetized



(Schaeffer et al., 2017) ✓

Electromagnetic shocks mediated by Weibel instabilities

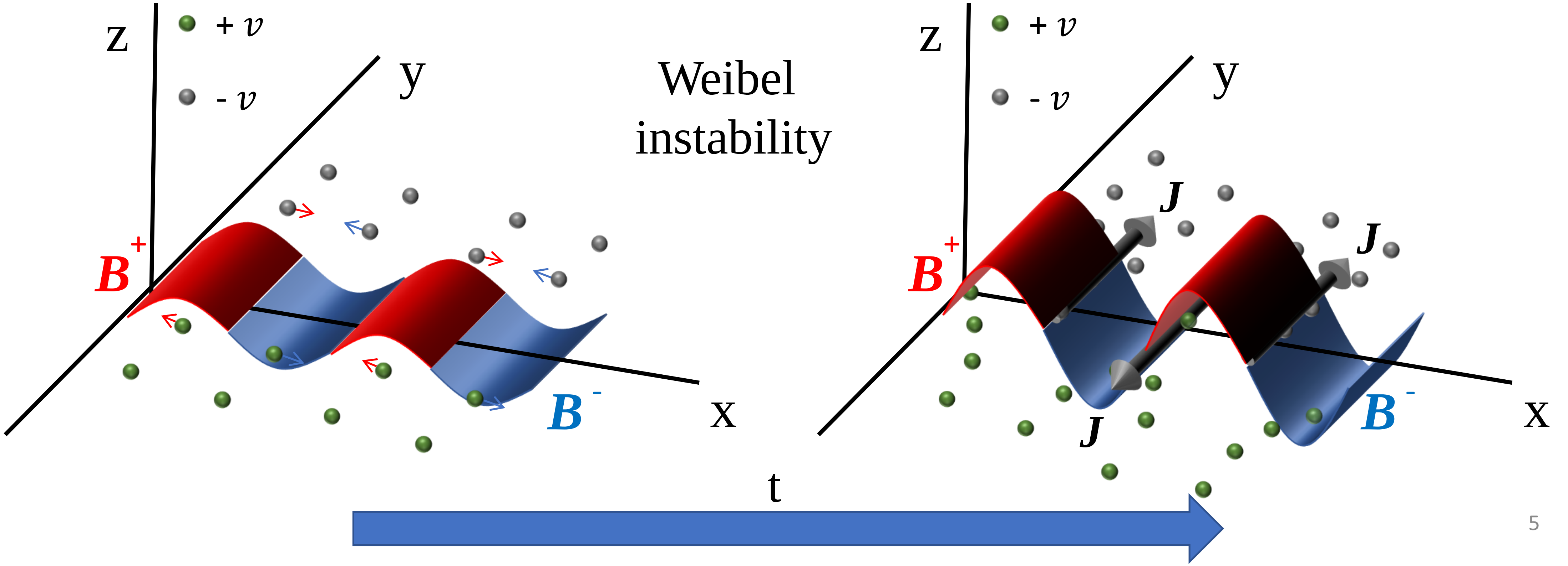
$$\boxed{\frac{\partial f_s}{\partial t} + \vec{v}\cdot\nabla_{\vec{r}} f_s + \frac{q_s}{m_s}\left(\vec{E} + \vec{v}\wedge\vec{B}\right)\cdot\nabla_{\vec{v}} f_s = 0,}$$

Linearization / Perturbation:

$$\{f_s, \vec{E}, \vec{B}\} = \{f_s{}^0, \vec{E}^0, \vec{B}^0\} + \{f_s{}^1, \vec{E}^1, \vec{B}^1\}$$

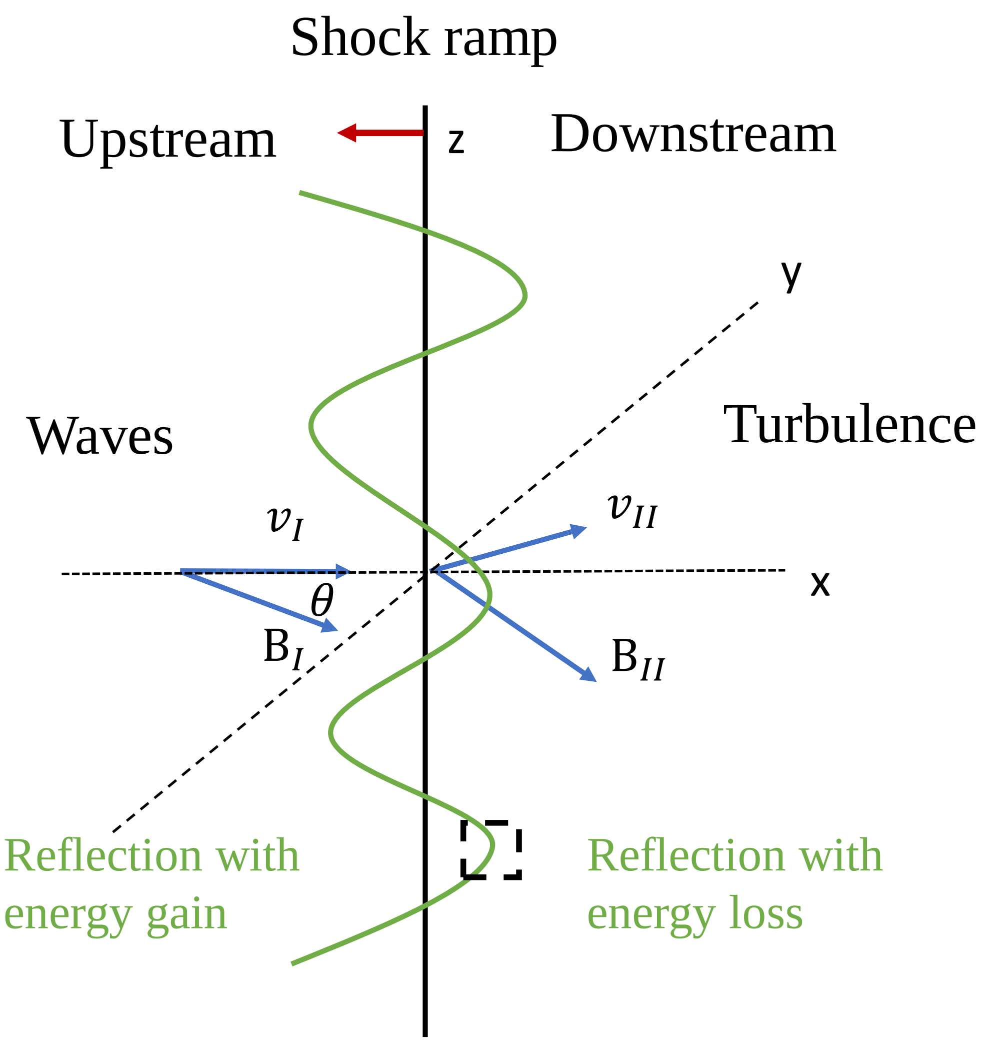
$$f_s{}^1 = \frac{i q_s/m_s}{\vec{v}\cdot\vec{k} - \omega}\left(\vec{E}^1 + \vec{v}\wedge\vec{B}^1\right)\cdot\nabla_{\vec{v}} f_s{}^0$$

with $\omega = \omega_r + i\,\delta$ → Growth rate

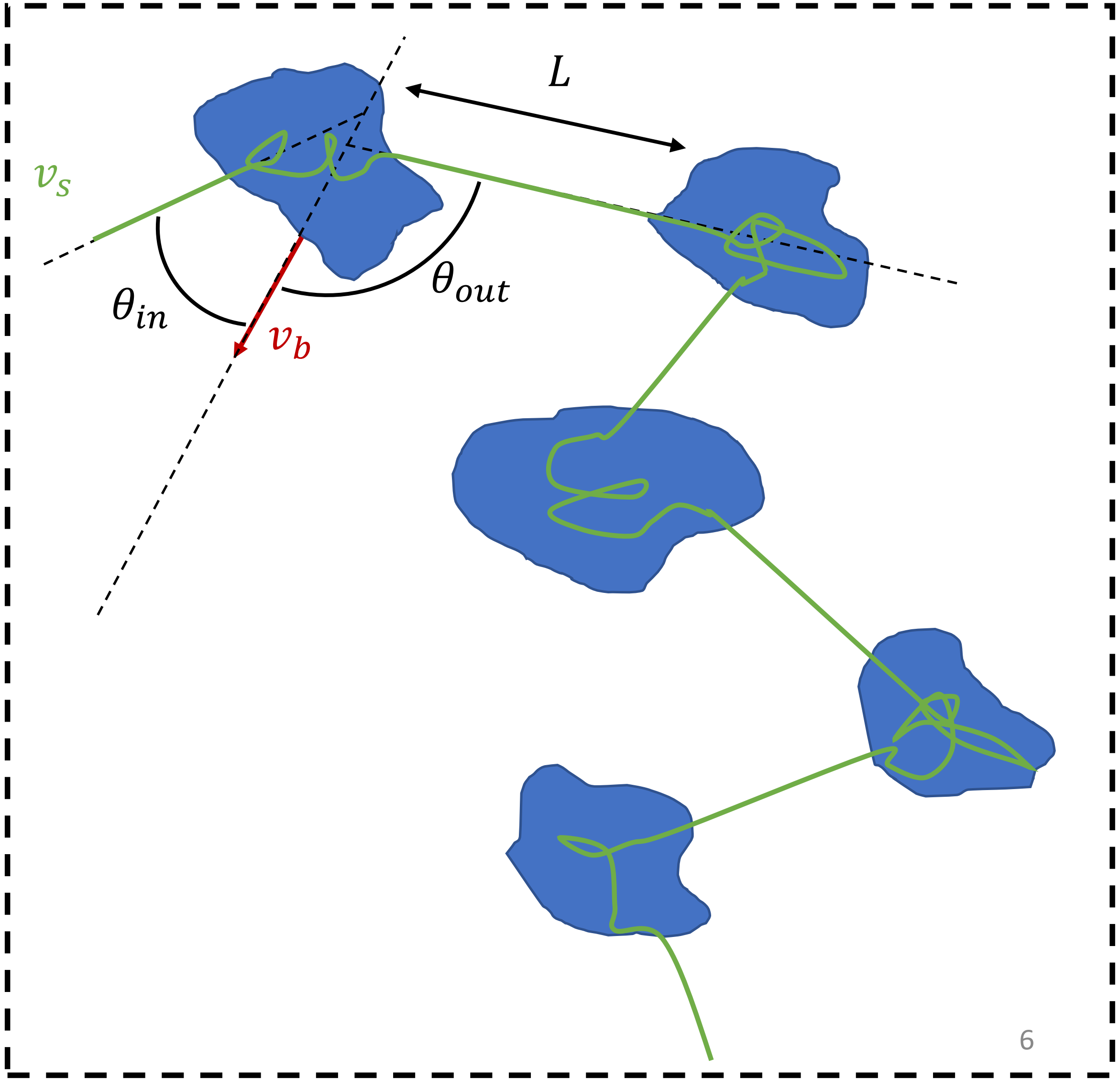


Weibel magnetic turbulence to Diffusion Shock Acceleration (DSA)

First order



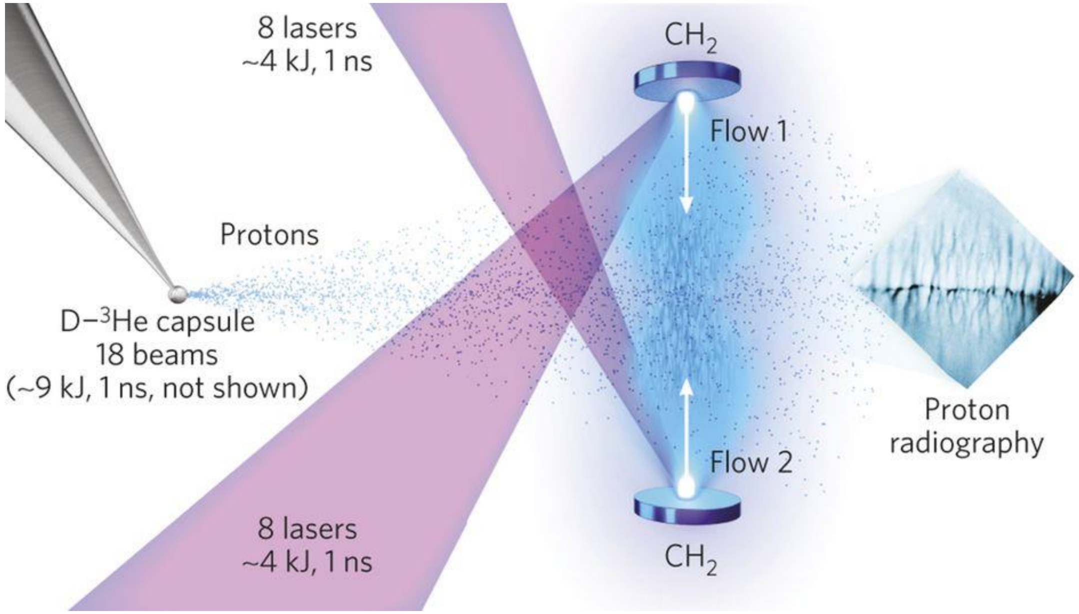
Second order



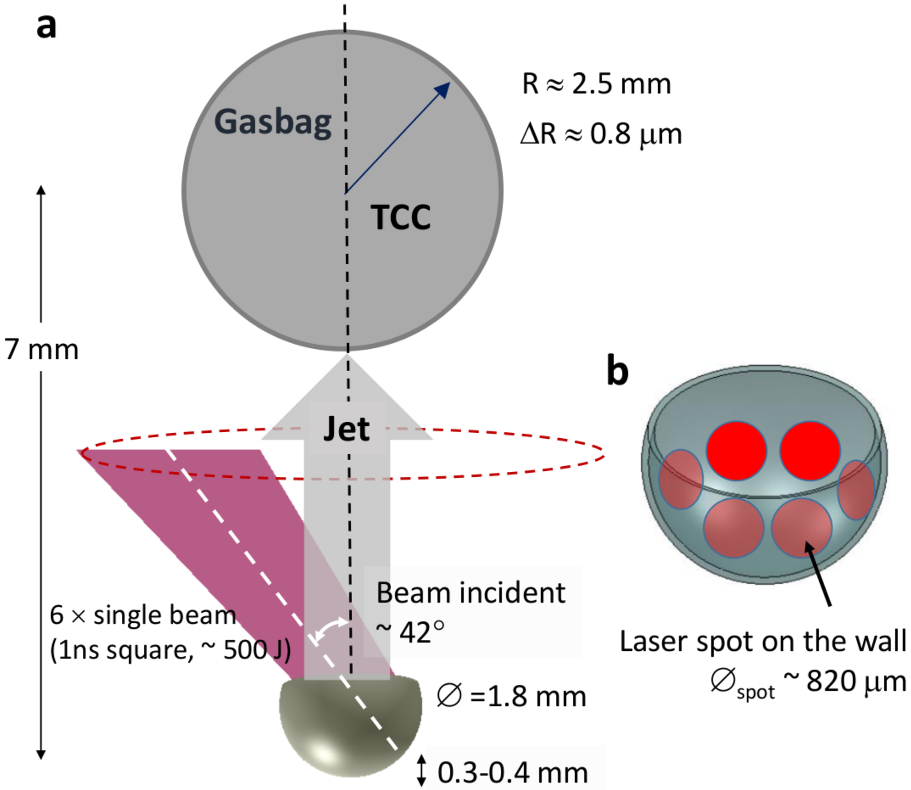
Electromagnetic shock on the OMEGA laser facility

Collisionless shock formation conditions

$$\lambda_{mfp} > \lambda_{sys} > L_{iso}$$



(Huntington et al., 2013, 2017)



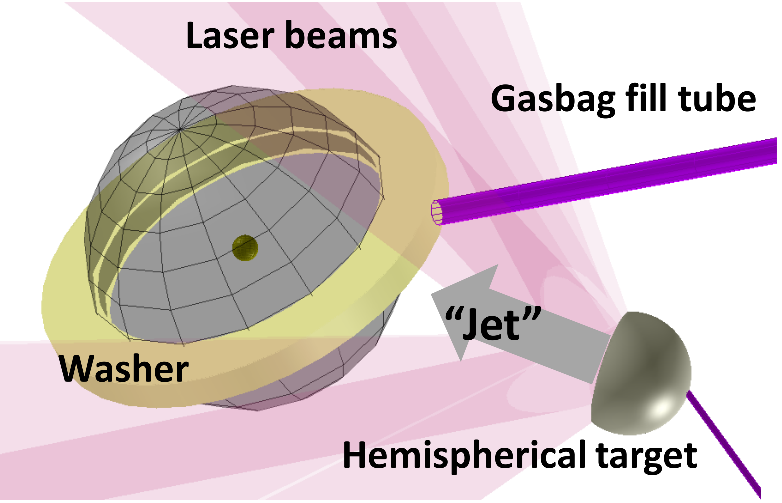
(Li et al., 2019)

No shock formation even after 6 ns of interaction.

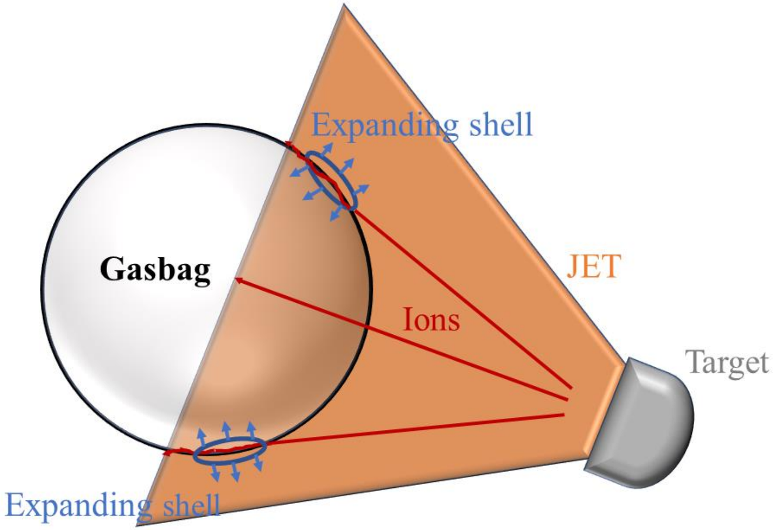
$$T_e = 40\ eV \qquad v_i = 1400\ km.s^{-1}$$

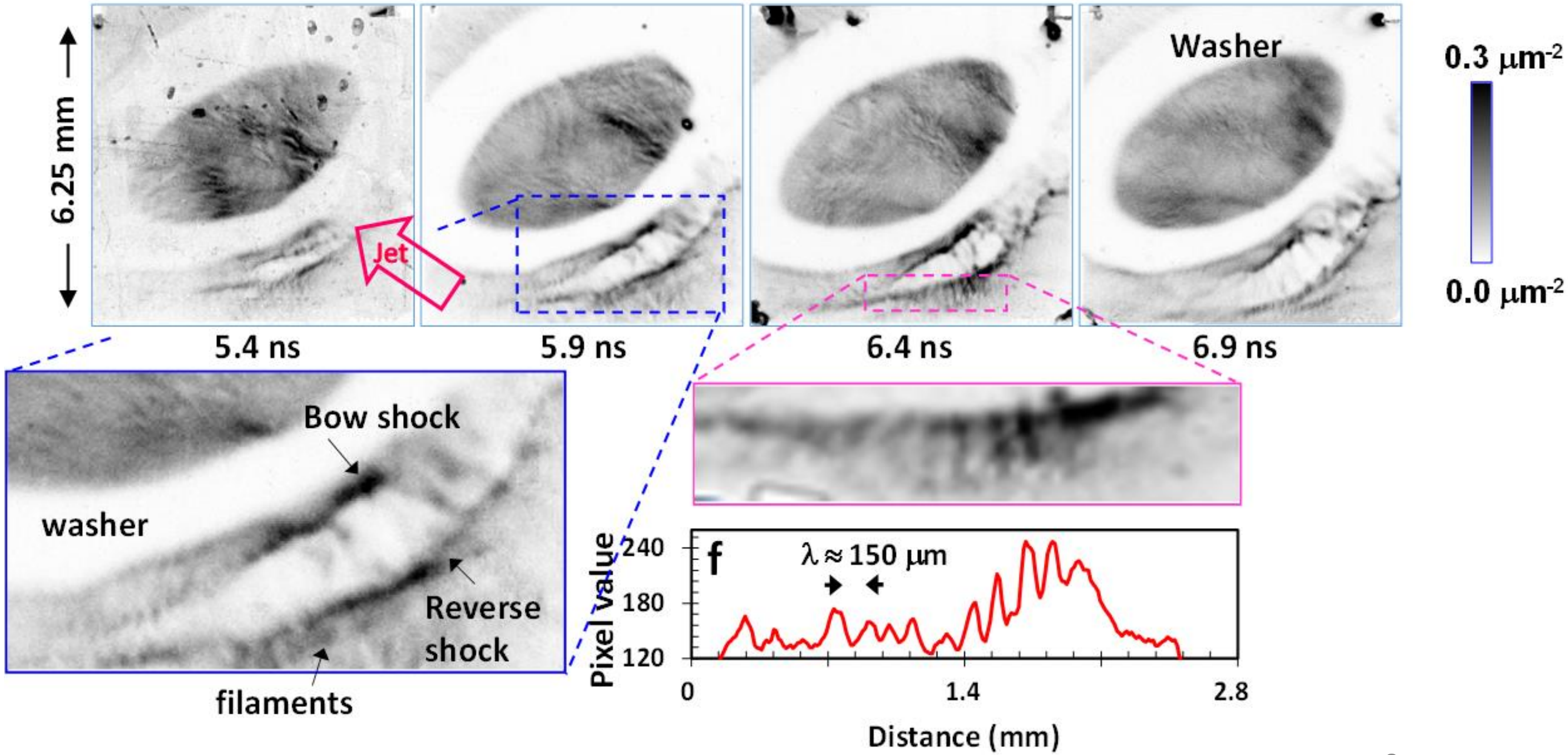
$$n_e = 5.10^{18}\ cm^{-3}$$

Experimental shock observation



- $r = \frac{V_1}{V_2} = \frac{N_2}{N_1} = 3$
- $M_I \approx 3$





(Li et al., 2019)

Magnetic piston ($\mu = 200$)

- $T_e = 10keV$
- $B_0 = 6.25 \times 10^{-2} B_r$
- $\beta = c_s^2 / v_A^2 \simeq 20$
- Normalization

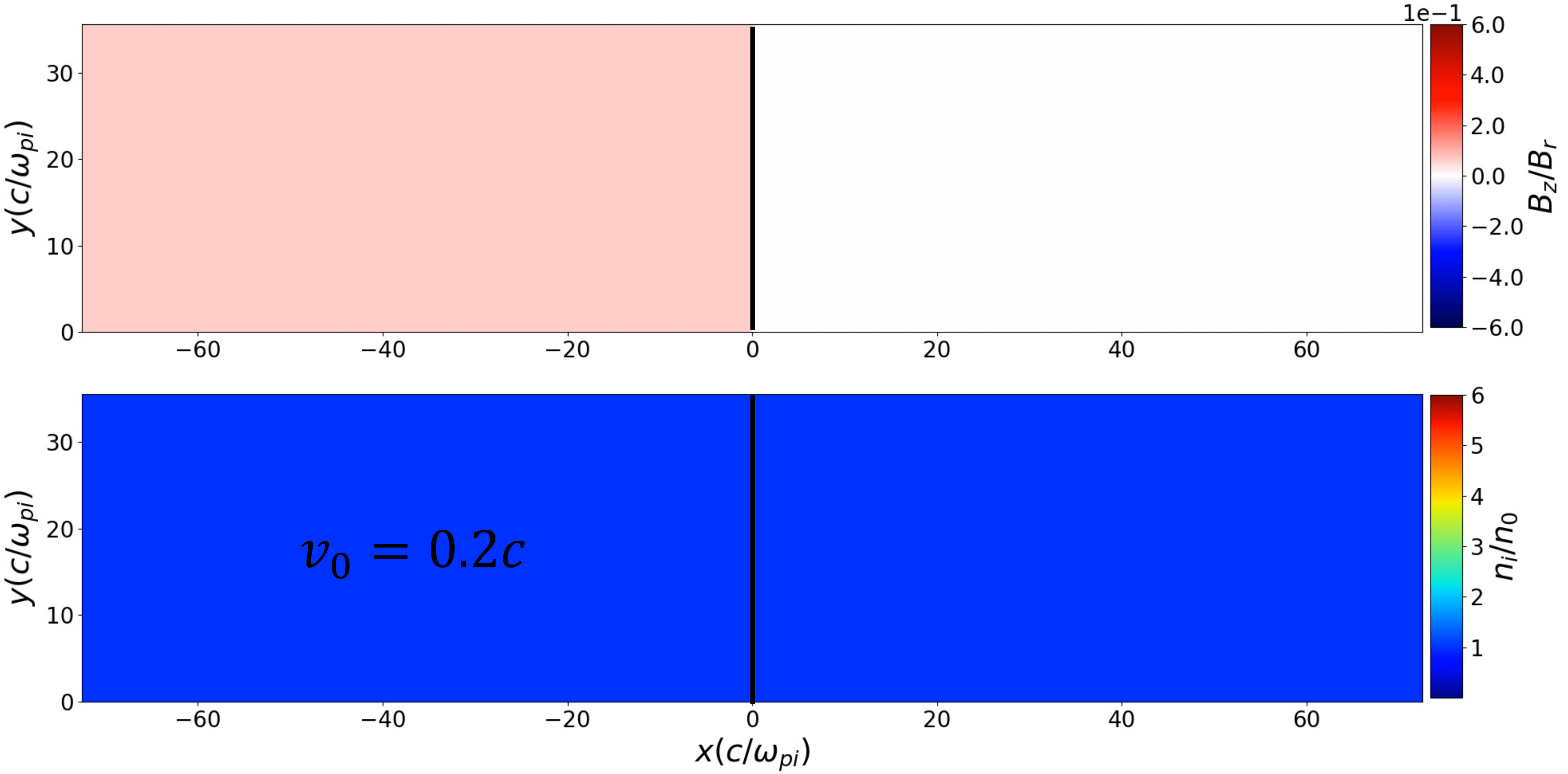
$$E_r = \frac{m_e c \omega_{pe}}{e} \qquad B_r = \frac{m_e \omega_{pe}}{e}$$

For $n_0 = 10^{18} cm^{-3}$

$B_r = 320$ T $\qquad \frac{c}{\omega_{pe}} = 5.6\ \mu m$

$E_r = 96$ GV/m $\qquad \omega_{pe}^{-1} = 18$ fs

- H^+: $m_i = 200\, m_e$



- Periodic boundaries (x,y)

Magnetic piston ($\mu = 200$)

Plasma 1: Ions move faster than the piston and propagate in Plasma 2 free of magnetic field.

Adiabatic compression:

$$n_{e3} = (1+R)n_{e1}$$
$$B_3 = (1+R)B_1$$
$$v_b = v_{i1}/(1+R)$$
$$T_{e3} = (1+2R/3)T_{e1}$$
$$R = N_2/N_1 = 1$$

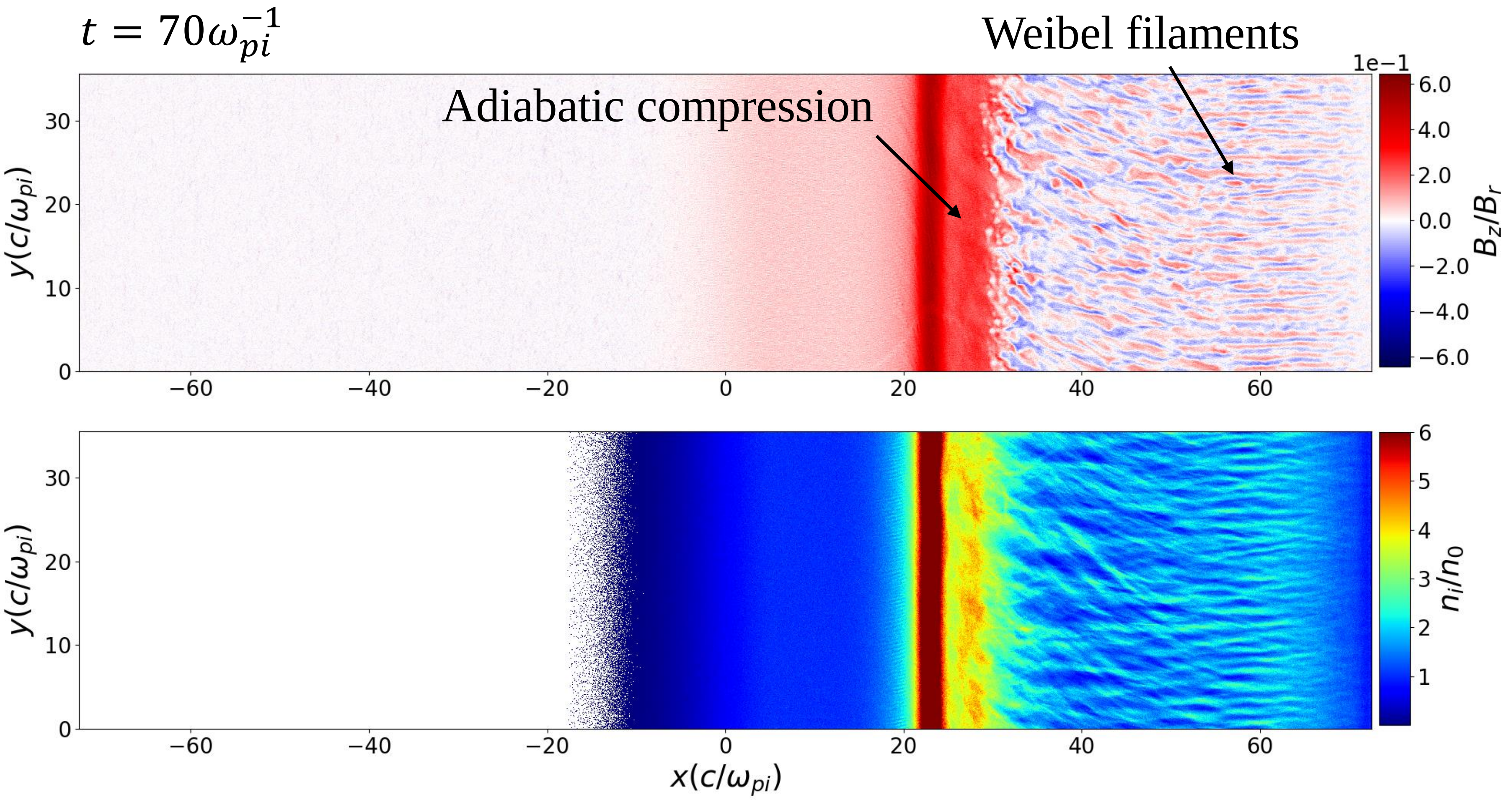
Weibel saturation:

$$\delta \simeq \sqrt{\frac{2\,T_{iy}}{\pi m_i}}\left|k_y\right|\frac{k_{max}^2 - k_y^2}{k_{max}^2}$$

$$k_{max} = \sqrt{a_i}\,\frac{\omega_{pi1}}{c}$$

$$a_i = \frac{K_{ix}}{K_{i\perp}} - 1 \qquad \tau_{sat} \cong \delta^{-1}$$

(Ruyer et al., 2015)



Magnetic piston ($\mu = 200$)

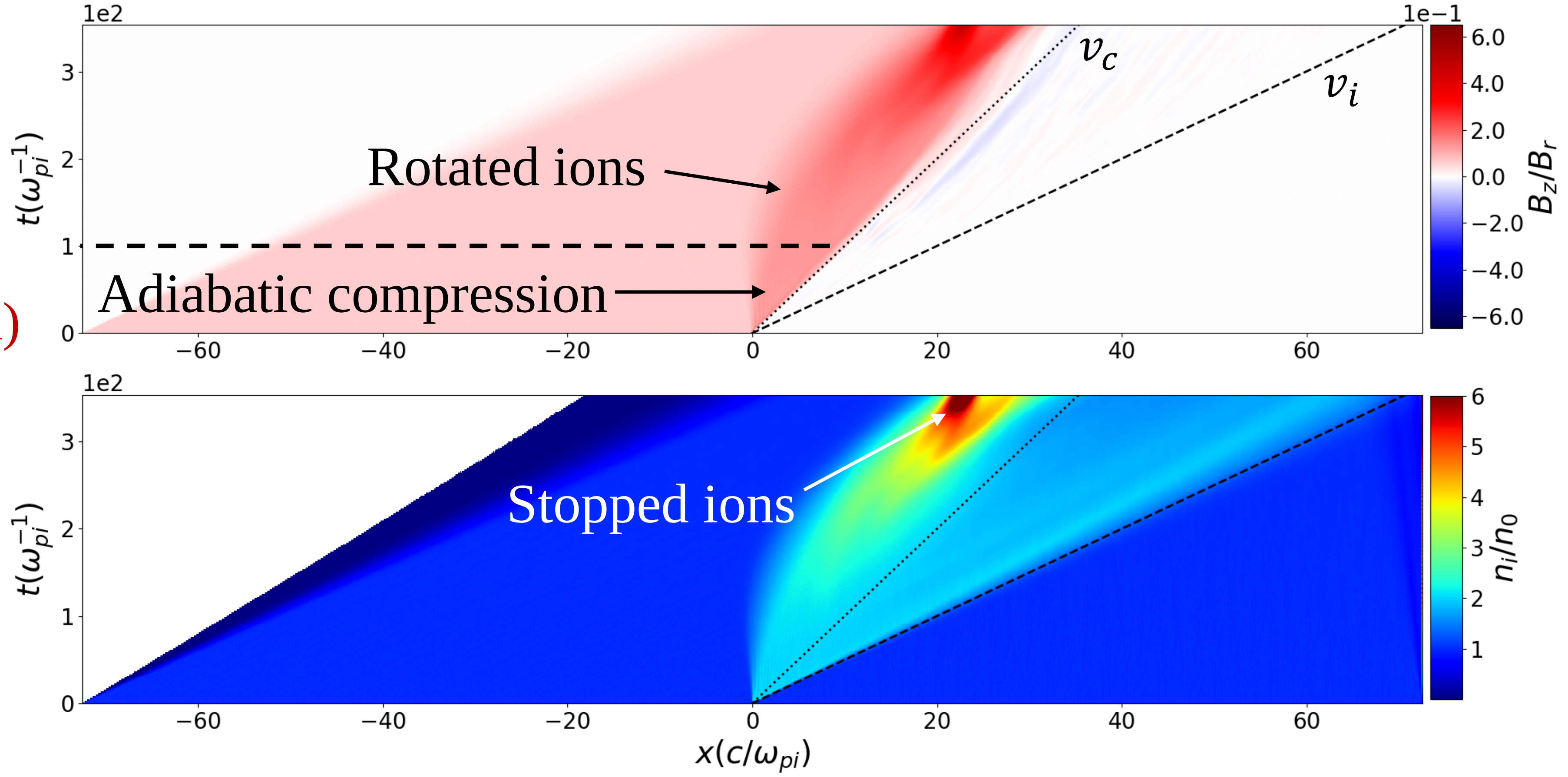
Plasma 1: Ions move faster than the piston and propagate in Plasma 2 free of magnetic field.

Adiabatic compression

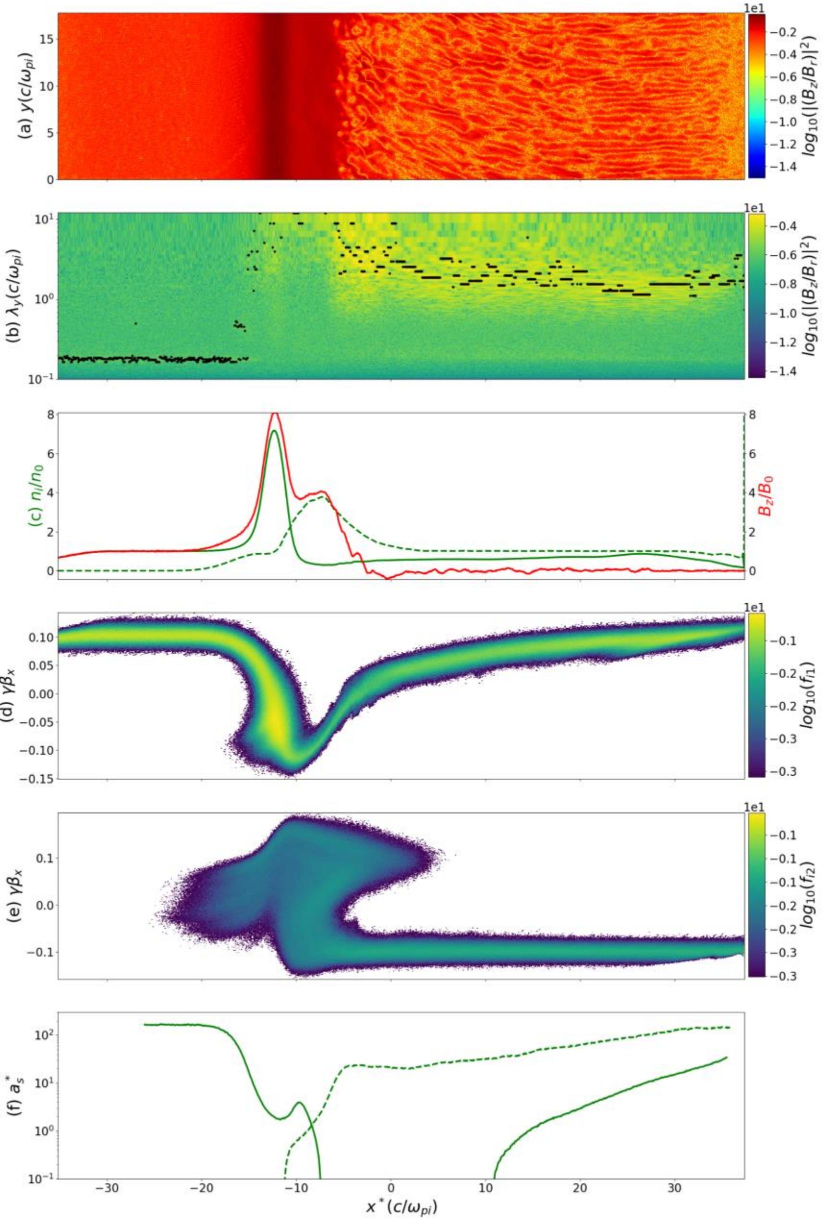
Ion rotation (magnetic piston)

Ions are stopped after:

$$t_p \sim \frac{\pi}{(1+R)\omega_{ci}} = \pi \frac{B_r}{B_3} \sqrt{\mu}\omega_{pi}^{-1}$$



Magnetic piston ($\mu = 200$)



- Plasma 1:

  Anisotropy decreases sharply (ions rotation)

  $$L_{iso}^{simu} < 50\ c.\omega_{pe}^{-1}$$

- Plasma 2:

  Magnetic filaments coalescence and turn out to turbulence

  Transverse heating reduce the anisotropy

  Weibel mediated shock: (Ruyer et al., 2017)

  $$L_{iso}^{th} \cong 35\left(\frac{m_i}{Z_i m_e}\right)^{0.4} c.\omega_{pi}^{-1} = 520c.\omega_{pe}^{-1} \gg L_{iso}^{simu}$$

- Forward shock mediated by both:
  - Weibel instability
  - Ion rotation into the magnetic piston

Time shocks formation

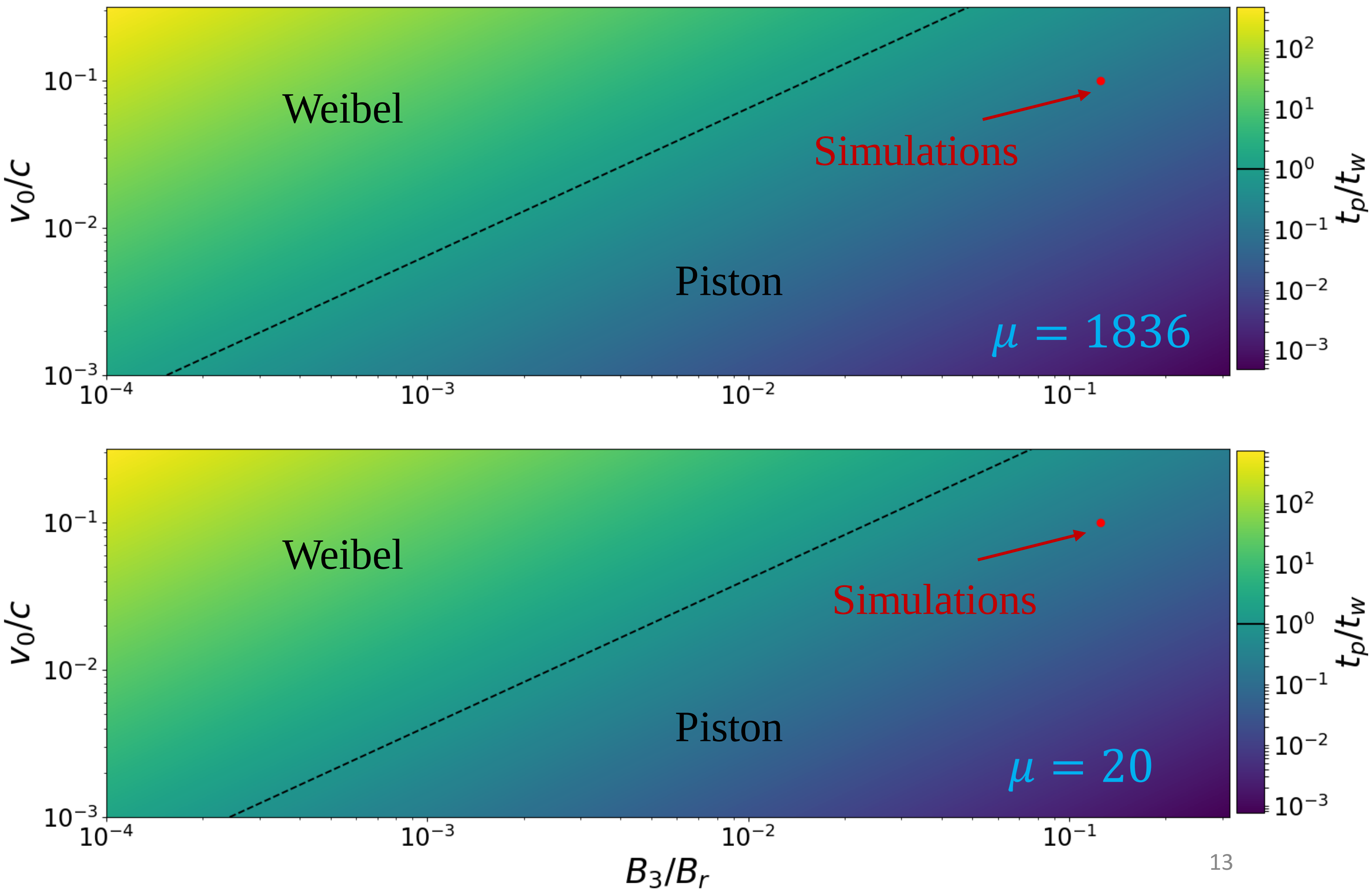
$$t_w \sim \frac{L_{iso}}{v_0} \cong 35\frac{c}{v_0}\left(\frac{\mu}{Z_i}\right)^{0.4} \omega_{pi}^{-1}$$

$$t_p \sim \frac{\pi}{(1+R)\omega_{ci}} = \pi\frac{B_r}{B_3}\sqrt{\mu}\omega_{pi}^{-1}$$

Simulations:

Ion rotation appears first

μ thinly affect the time shock formation ratio



Magnetic piston ($\mu = 20$)

- H^+: $m_i = 20\, m_e$

- $T_e = 10keV$
- $B_0 = 6.25 \times 10^{-2} B_r$
- $\beta = c_s^2 / v_A^2 \simeq 20$

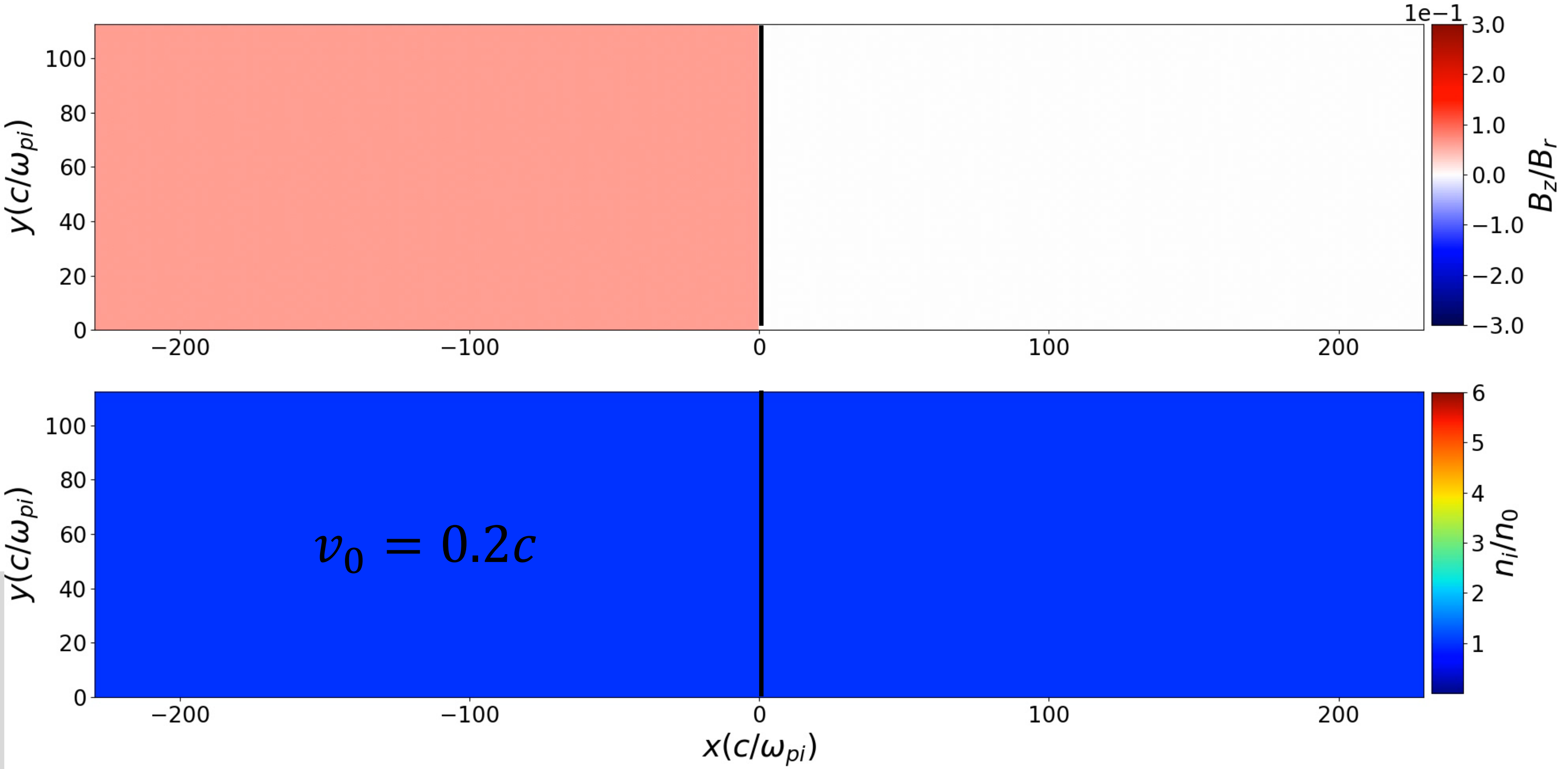
- Normalization

$$E_r = \frac{m_e c \omega_{pe}}{e} \qquad B_r = \frac{m_e \omega_{pe}}{e}$$

For $n_0 = 10^{18} cm^{-3}$

$B_r = 320$ T $\qquad \frac{c}{\omega_{pe}} = 5.6\ \mu m$

$E_r = 96$ GV/m $\qquad \omega_{pe}^{-1} = 18$ fs



- Periodic boundaries (x,y)

Larger time shock evolution ($\mu = 20$)

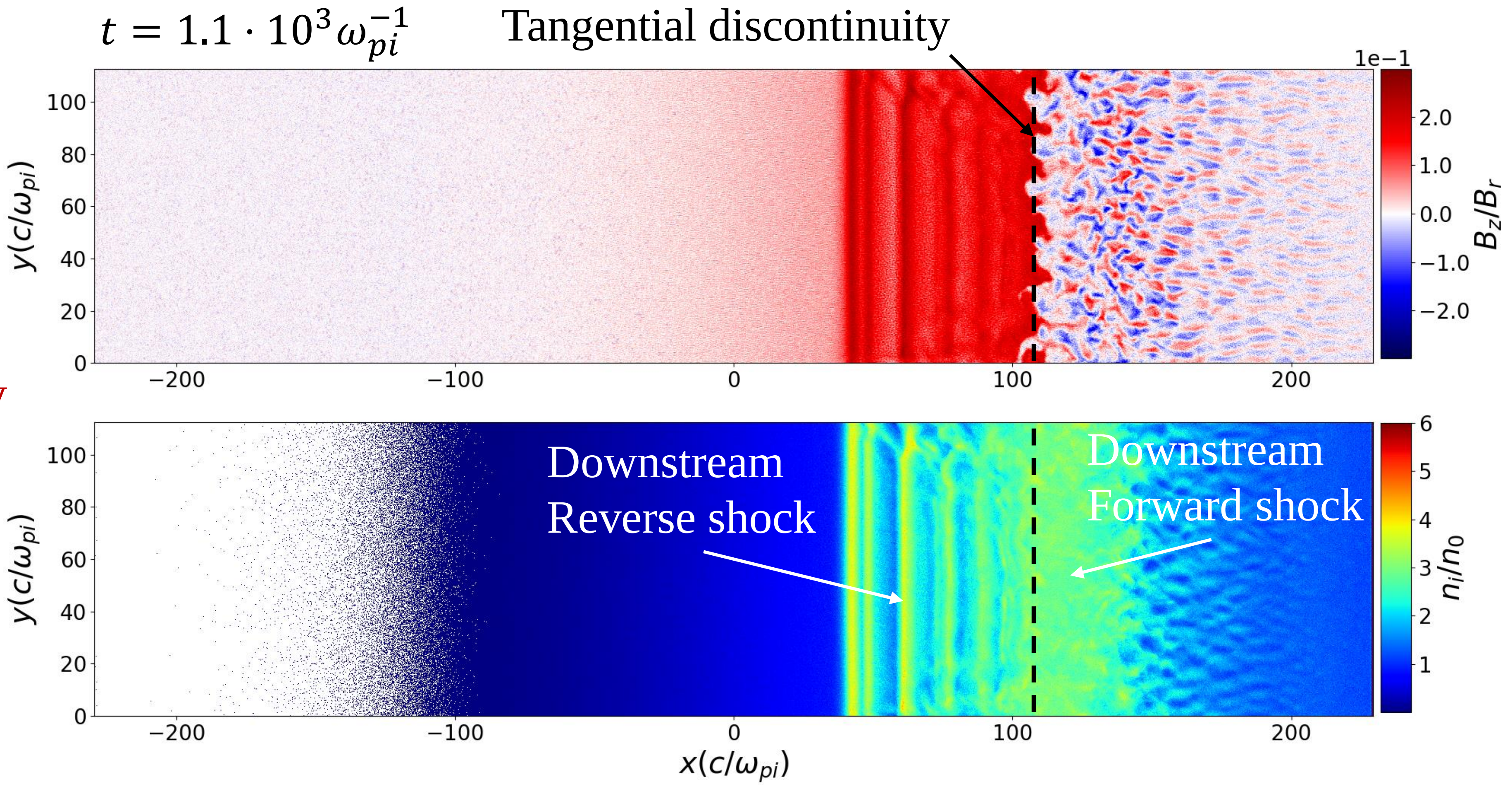
- Reverse shock:

  Fast magnetosonic waves

- Tangential discontinuity

- Forward shock:

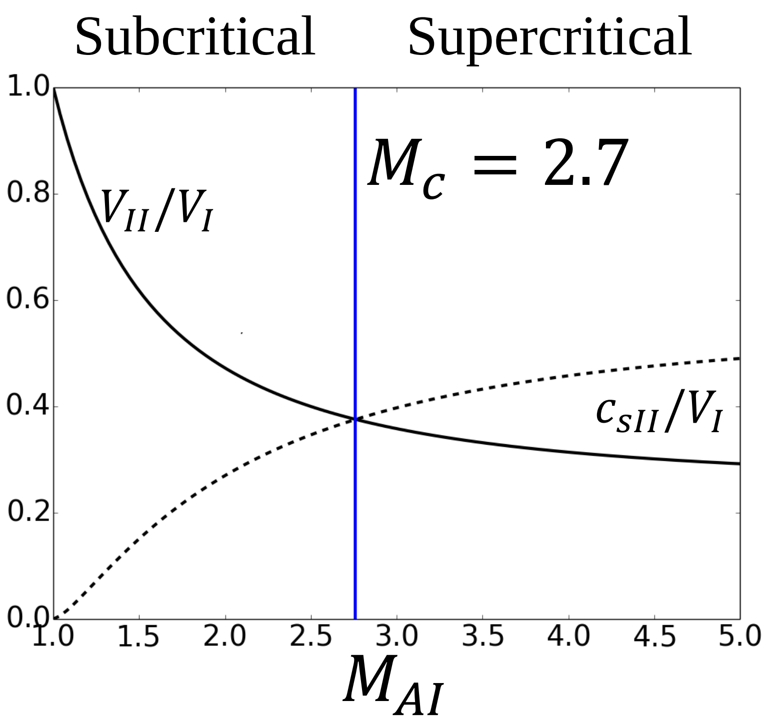
  Magnetic turbulence



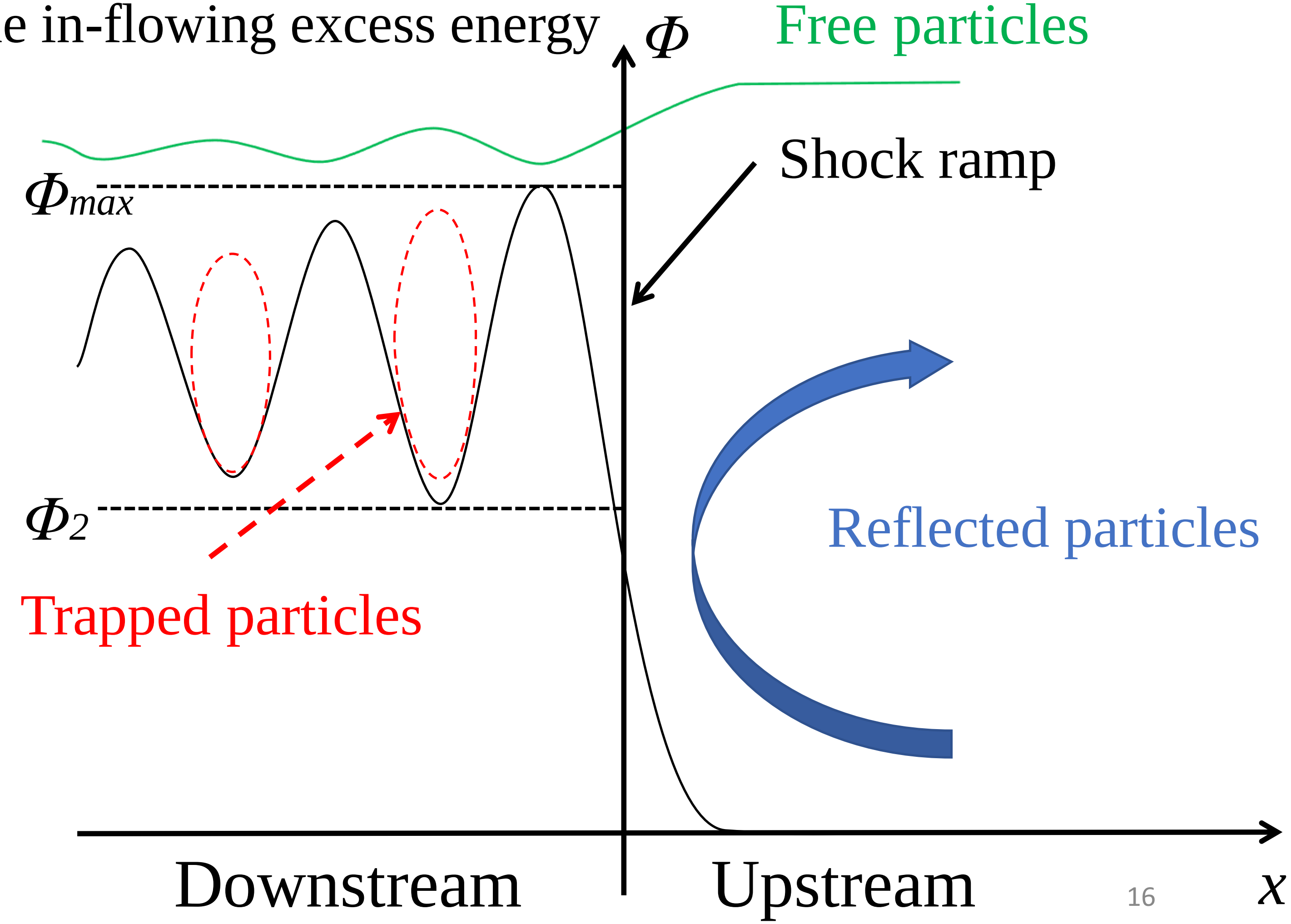
Collisionless shock properties: Criticality

- Subcritical shock: wave-particle interaction enough for dissipation
- Supercritical shock: needs rejection of the in-flowing excess energy

↳ Self-reformation



(Marshall, 1955)



Shock propagation ($\mu = 20$)

- Reverse shock:

$$v_r^* \simeq -\frac{v_i}{3}$$

$$M_{rA} = \frac{|v_i - (v_c + v_r^*)|}{v_A} = 12$$

$$M_{rA} > M_c = 2.3$$

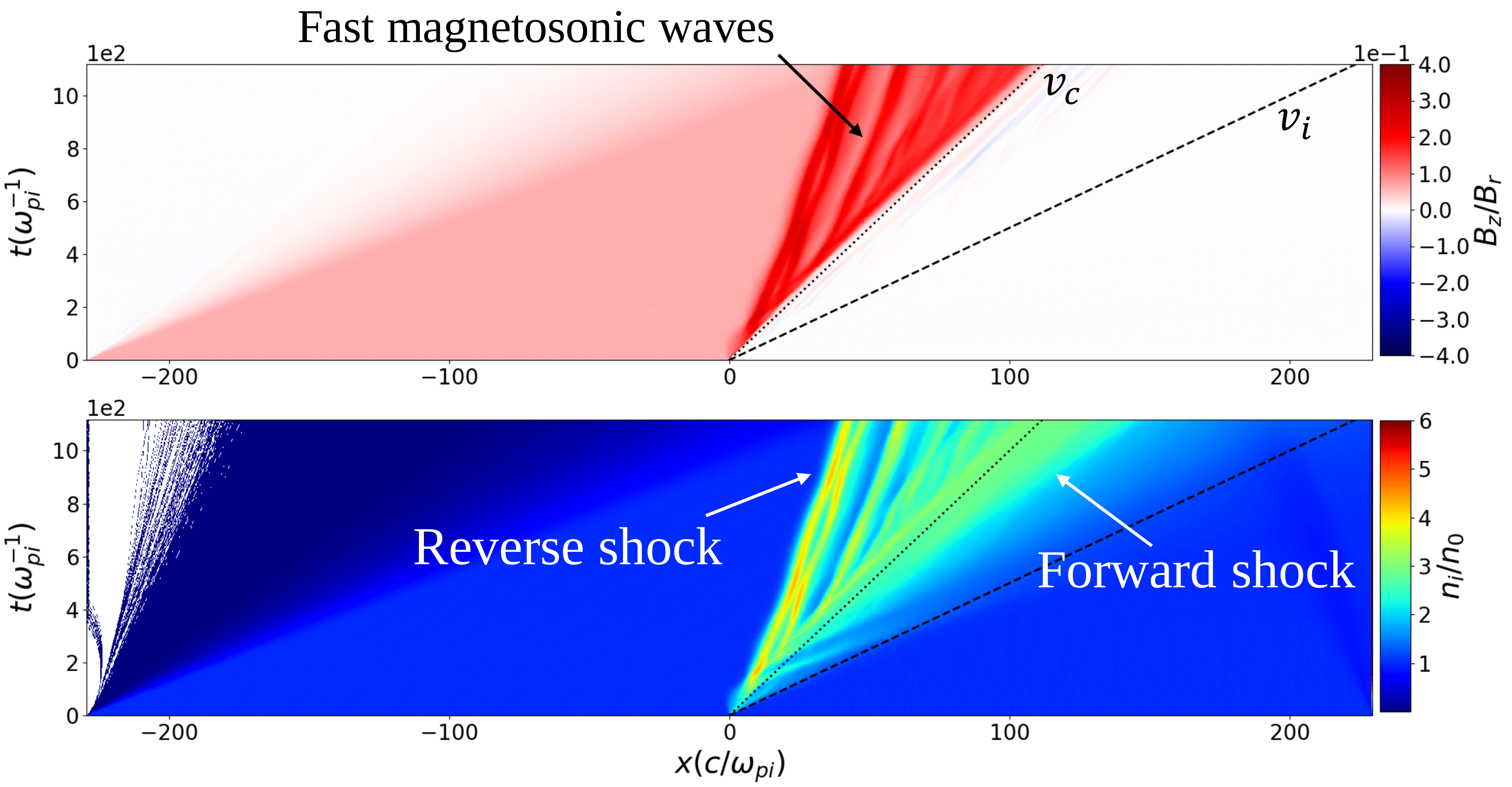
- Forward shock:

$$v_f^* \simeq \frac{v_i}{5}$$

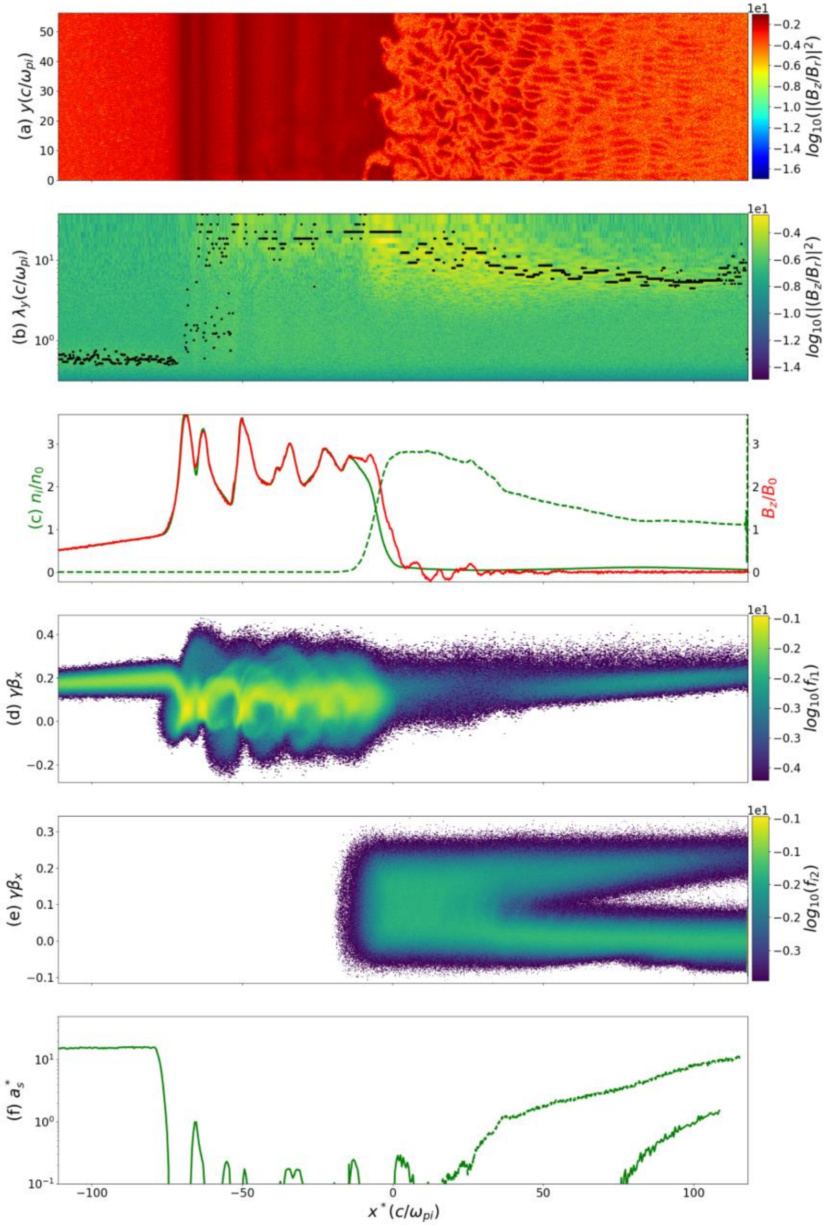
$$M_f = \frac{|v_c + v_f^*|}{c_s} \simeq 0.7\sqrt{\mu}$$

$$M_f > 1$$

Both shocks are Supercritical



Anisotropy ($\mu = 20$)



- Tangiential discontinuity unstable:

  Magnetic mirror edge instability (Korneev 2014)

- MHD jump conditions:

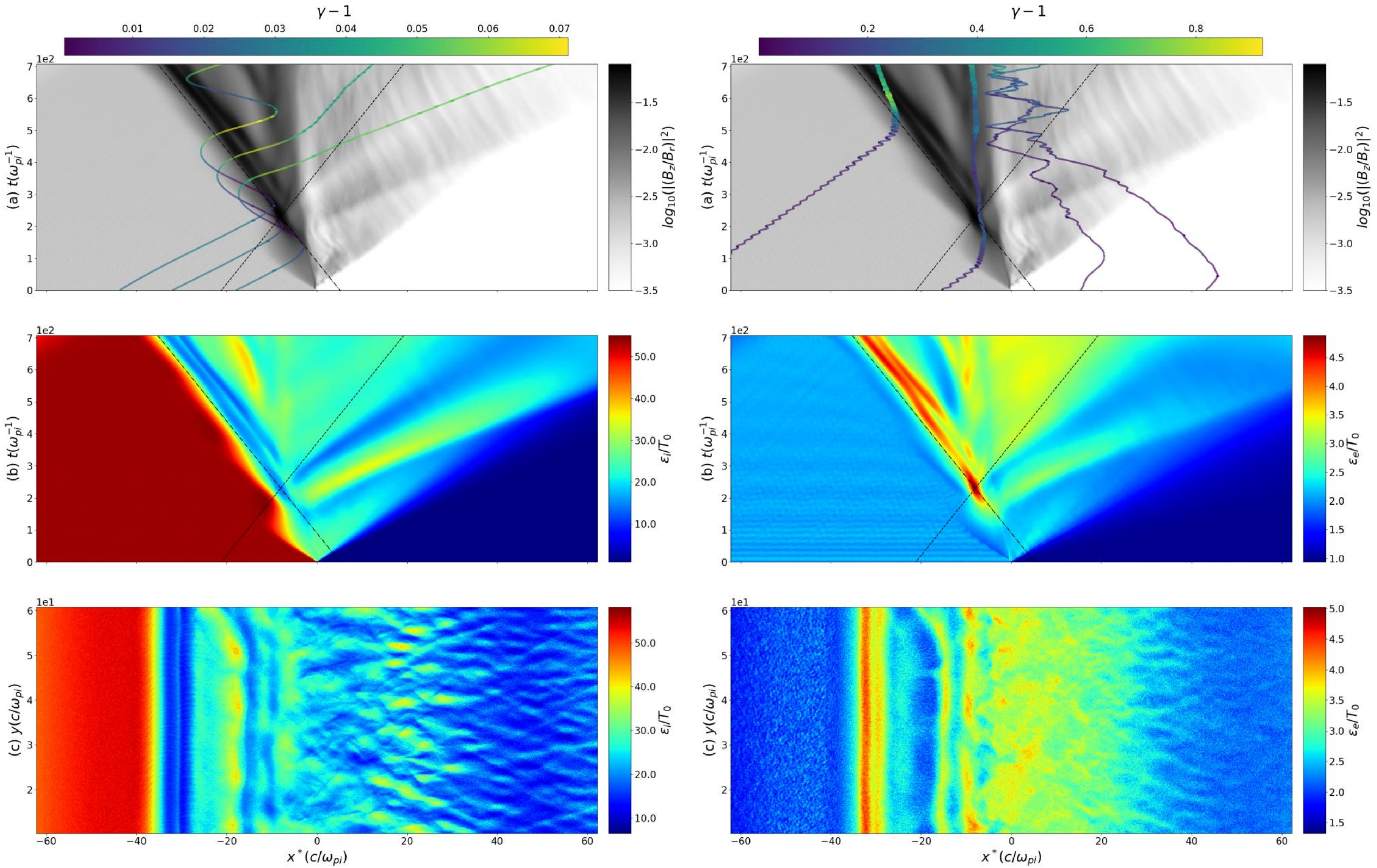
$$\Delta_r = \frac{2(\Gamma+1)}{D+\sqrt{D^2+4(\Gamma+1)(2-\Gamma)M_{AI}^{-2}}} = \frac{v_I}{v_{II}} = \frac{\mathrm{N}_{II}}{\mathrm{N}_I} = \frac{\mathrm{B}_{II}}{\mathrm{B}_I}$$

$$D = (\Gamma - 1) + (2M_I^{-2} + \Gamma M_{AI}^{-2})$$

- Anisotropy:

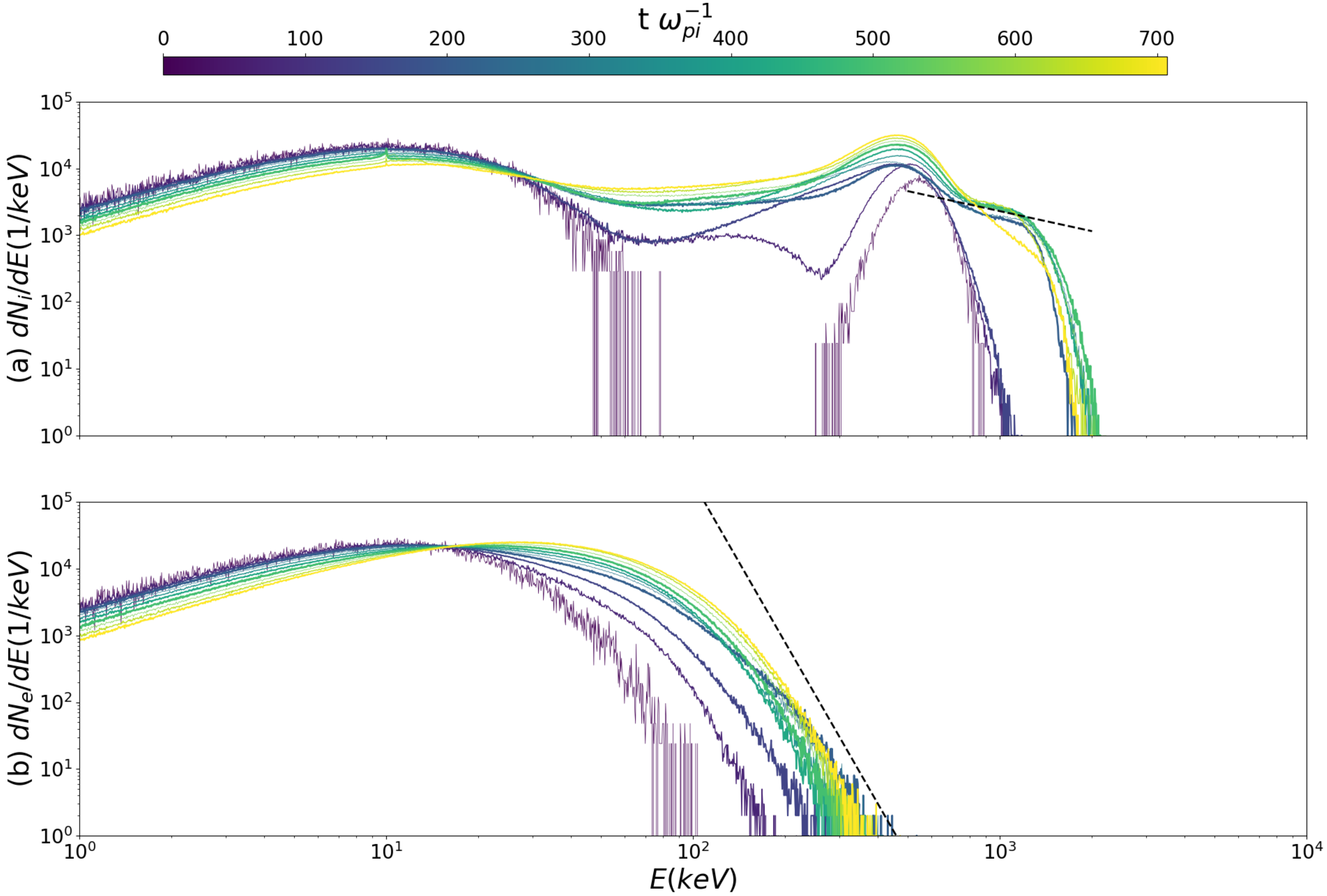
  Forward shock only mediated by Weibel instability

Particle acceleration ($\mu = 50$)



- Forward shock
  - Protons:
    Diffusion upstream
  - Electrons:
    Heating up to a factor 3
- Reverse shock
  - Protons:
    Cyclontron wave
    acceleration
  - Electrons:
    Heating up to a factor 5

Particles Fermi acceleration in the forward shock ?



Proton acceleration

$$\frac{dN_i}{dE} \propto E^{-1}$$ Fermi II

Electron heating

Conclusions

Magnetic piston

- Adiabatic compression leads to a separation between magnetic field front and ion front.
- Growth of the Weibel instability upstream between the two fronts.

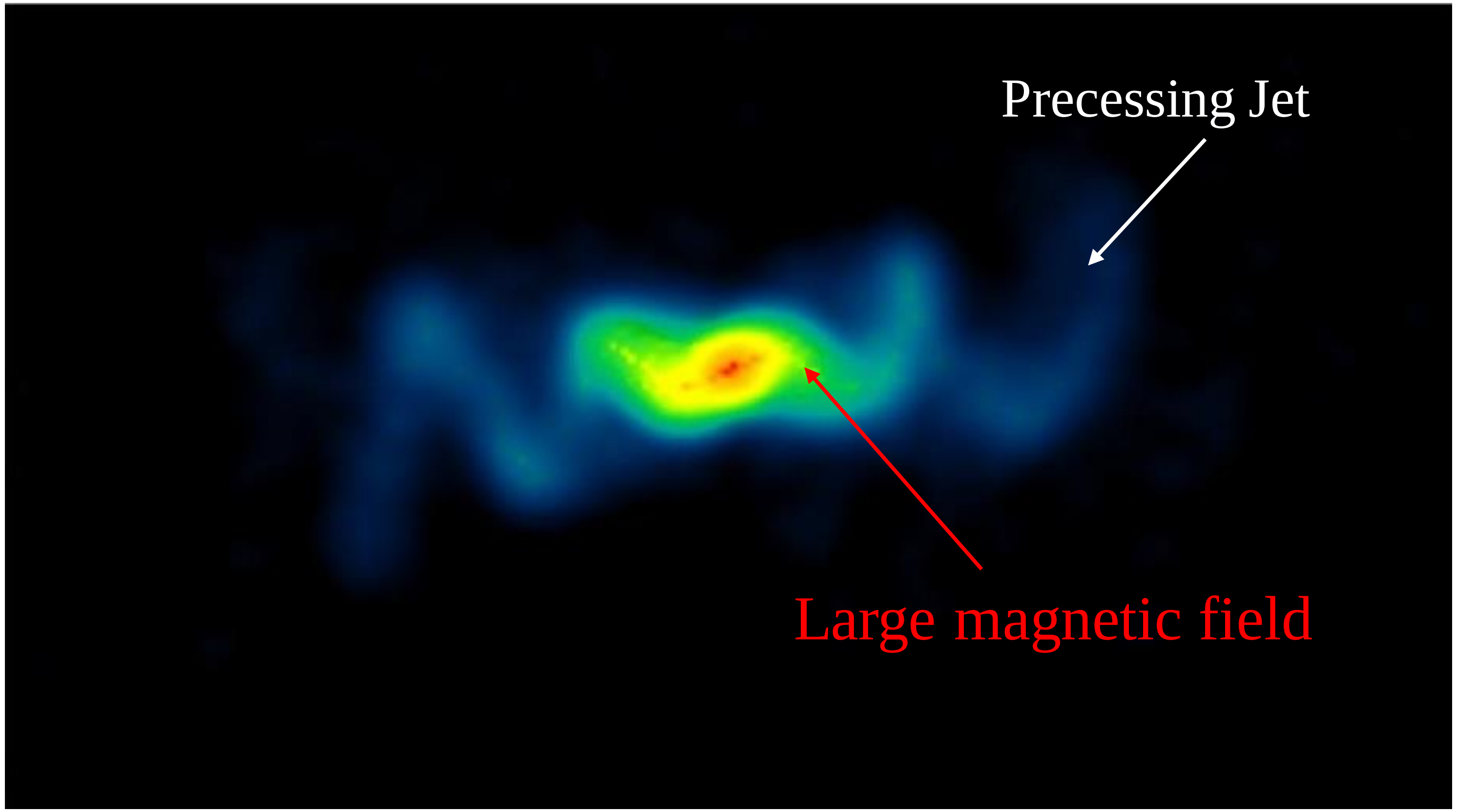
Shocks

- Reverse fast magnetosonic shock: magnetized with cyclontron wave: proton acceleration.
- Forward shock: electromagnetic with upstream turbulence
  Proton acceleration by Fermi II?
- Tangential discontinuity between the two downstream region: mirror edge instability

Thanks for your attention

Magnetic field?

Credit: Blundell & Bowler, NRAO/AUI/NSF



Jet SS433

- Micro-quasar

$M_{\mathrm{BH}} \sim 10\ M_{\mathrm{sun}}$

$v_{\mathrm{jet}} = c/3$

$\beta = \frac{c_s^2}{v_A^2} =?$

Weibel mediated shock

- $T_e = 10keV$
- H^+: $m_i = 20\, m_e$
- Periodic boundaries (x,y)
- Normalization

$t = \omega_{pe}^{-1}$ $\quad x = c.\omega_{pe}^{-1}$

$E_r = \frac{m_e c \omega_{pe}}{e}$ $\quad B_r = \frac{m_e \omega_{pe}}{e}$

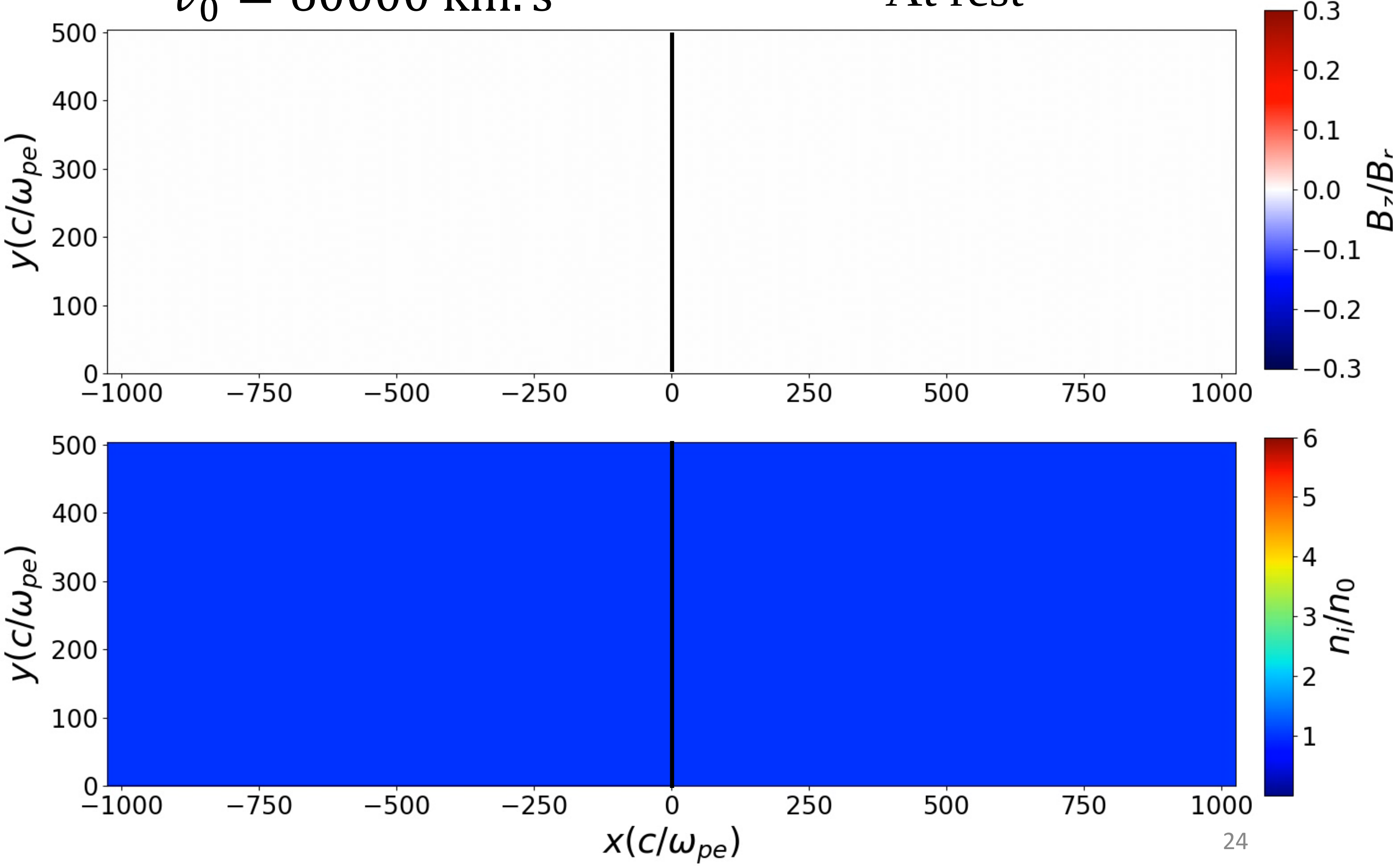
For $n_0 = 10^{18} cm^{-3}$

$B_r = 320$ T $\quad \frac{c}{\omega_{pe}} = 5.6\ \mu m$

$E_r = 96$ GV/m $\quad \omega_{pe}^{-1} = 18$ fs

Plasma 1
$v_0 = 60000\ \mathrm{km.s^{-1}}$

Plasma 2
At rest



Weibel mediated shock

Weibel saturation:

$$\delta \simeq \sqrt{\frac{2\,T_{iy}}{\pi m_i}}\left|k_y\right|\frac{k_{max}^2 - k_y^2}{k_{max}^2}$$

$$k_{max} = \sqrt{a_i}\,\frac{\omega_{pi1}}{c}$$

$$a_i = \frac{m_i(v_{ix} - v_c)^2 + T_{ix}}{T_{i\perp}} - 1$$

$\tau_{sat} \cong \delta^{-1}$ (Ruyer et al., 2015)

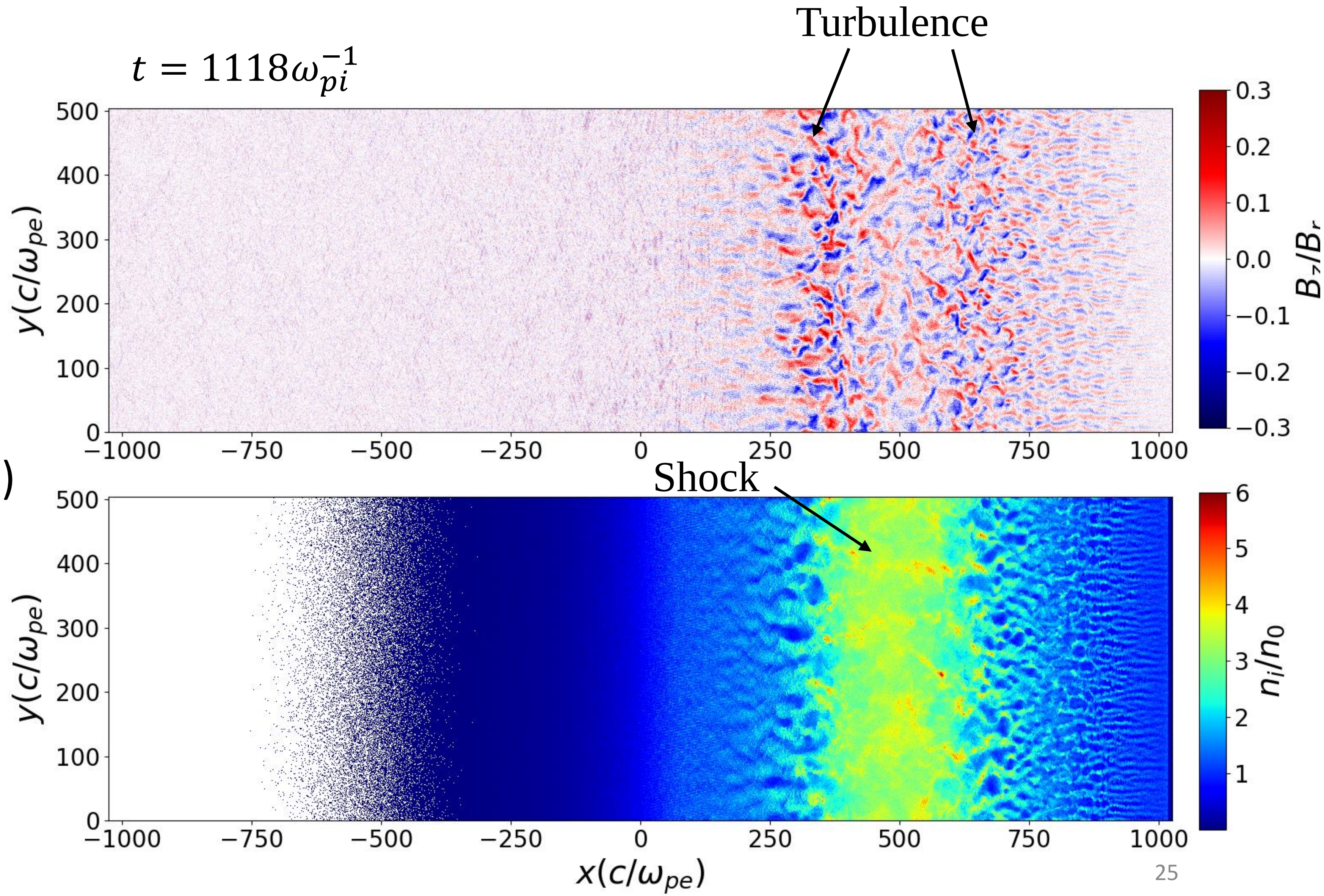
Rankine-Hugoniot:

$$r = \frac{(\Gamma + 1)}{(\Gamma - 1) + 2M_I^{-2}} = \frac{v_I}{v_{II}} = \frac{\mathrm{N}_{II}}{\mathrm{N}_I}$$

$$\Gamma = 1 + \frac{2}{n} \longrightarrow r = 3$$

Degrees of freedom

$t = 1118\omega_{pi}^{-1}$



Weibel mediated shock

- Speed of the center mass:

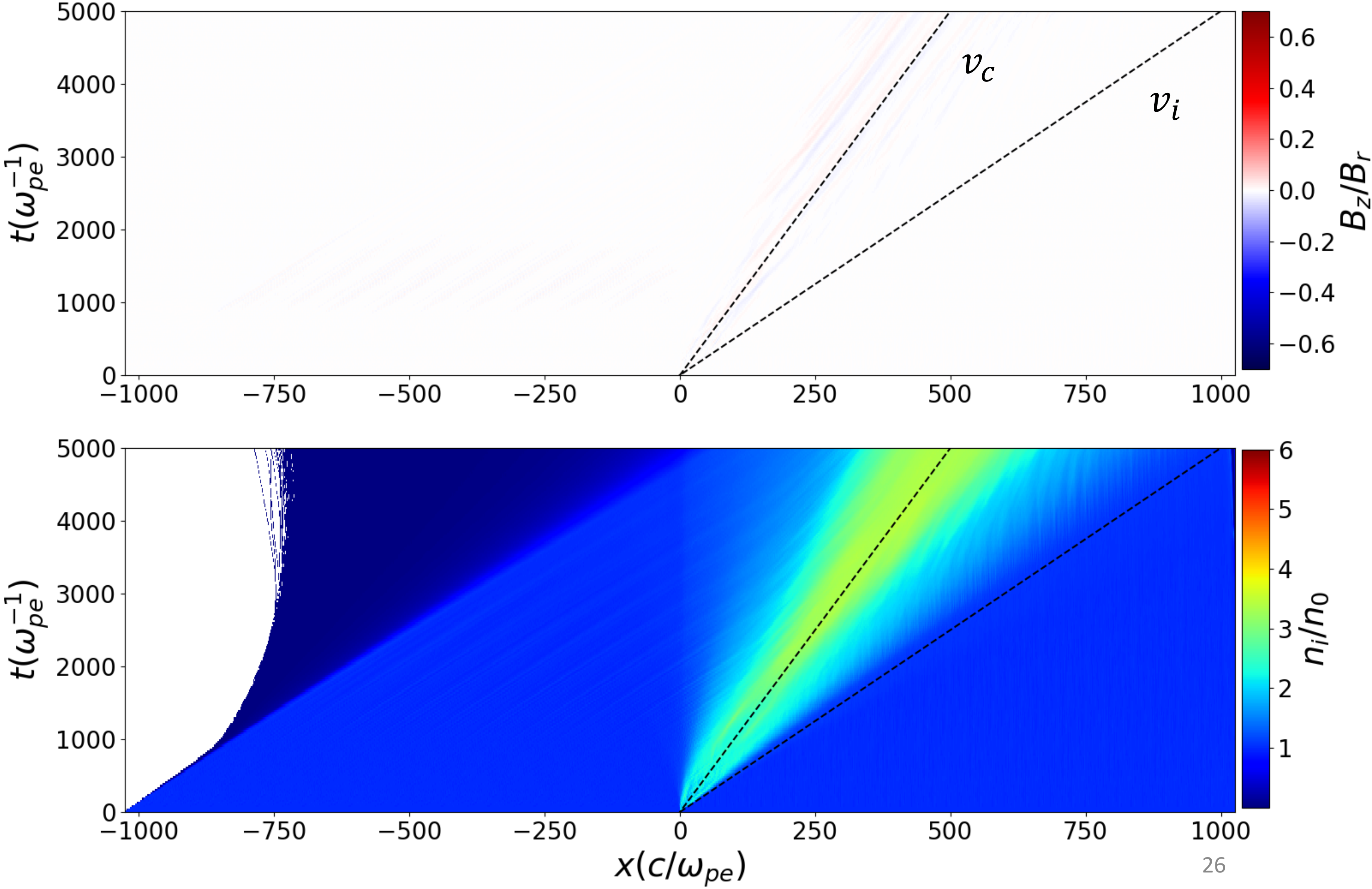
$$v_c = \frac{1}{2} v_i$$

- Speed of the reflected ion beam:

$$v_b = v_i$$

- Shocks speed in the center mass frame:

$$v_f^* = \frac{1}{6} v_i \quad v_r^* = -\frac{1}{6} v_i$$



Magnetic piston

Parameter	Initial value
$\omega_{pe} = \sqrt{n_0 e^2/\epsilon_0\, m_e}$	*unknow*
$\omega_{ce} = eB_1/m_e$	$6.25 \cdot 10^{-2}\omega_{pe}$
$\omega_{pi} = \sqrt{n_0 Z_i e^2/\epsilon_0\, m_i}$	$(1/\sqrt{\mu})\omega_{pe}$
$\omega_{ci} = eZ_iB_1/m_i$	$(1/\mu) \times 6.25 \cdot 10^{-2}\omega_{pe}$
$\omega_{LH} = \left((\omega_{ce}\omega_{ci})^{-1} + \omega_{pi}^{-2}\right)^{-1/2}$	$(1/\sqrt{\mu}) \times 6.25 \cdot 10^{-2}\omega_{pe}$
$r_e = v_0/\omega_{ce}$	$3.2\, c.\, \omega_{pe}^{-1}$
$r_i = v_0/\omega_{ci}$	$\mu \times 3.2\, c.\, \omega_{pe}^{-1}$
$\lambda_i \propto v_0^4 \mu^{\frac{3}{2}}/Z_i\omega_{pe}$	$\mu \times 1.5 \cdot 10^7 c.\, \omega_{pe}^{-1}$
$c_s = \left((\gamma_e T_e + \gamma_i T_i)/m_i\right)^{1/2}$	$(1/\sqrt{\mu}) \times 3.0 \cdot 10^{-1}c$
$v_A = B_1/(\mu_0 m_i n_0)^{1/2}$	$(1/\sqrt{\mu}) \times 6.25 \cdot 10^{-2}c$
$c_{ms} = (c_s^2 + v_A^2)^{1/2}$	$(1/\sqrt{\mu}) \times 3.1 \cdot 10^{-1}c$
$\beta = c_s^2/v_A^2$	~ 20

$$\mu = m_i/m_e$$

$$M_s = \sqrt{\mu} \times 6.7 \cdot 10^{-1}$$
$$M_A = \sqrt{\mu} \times 3.2$$

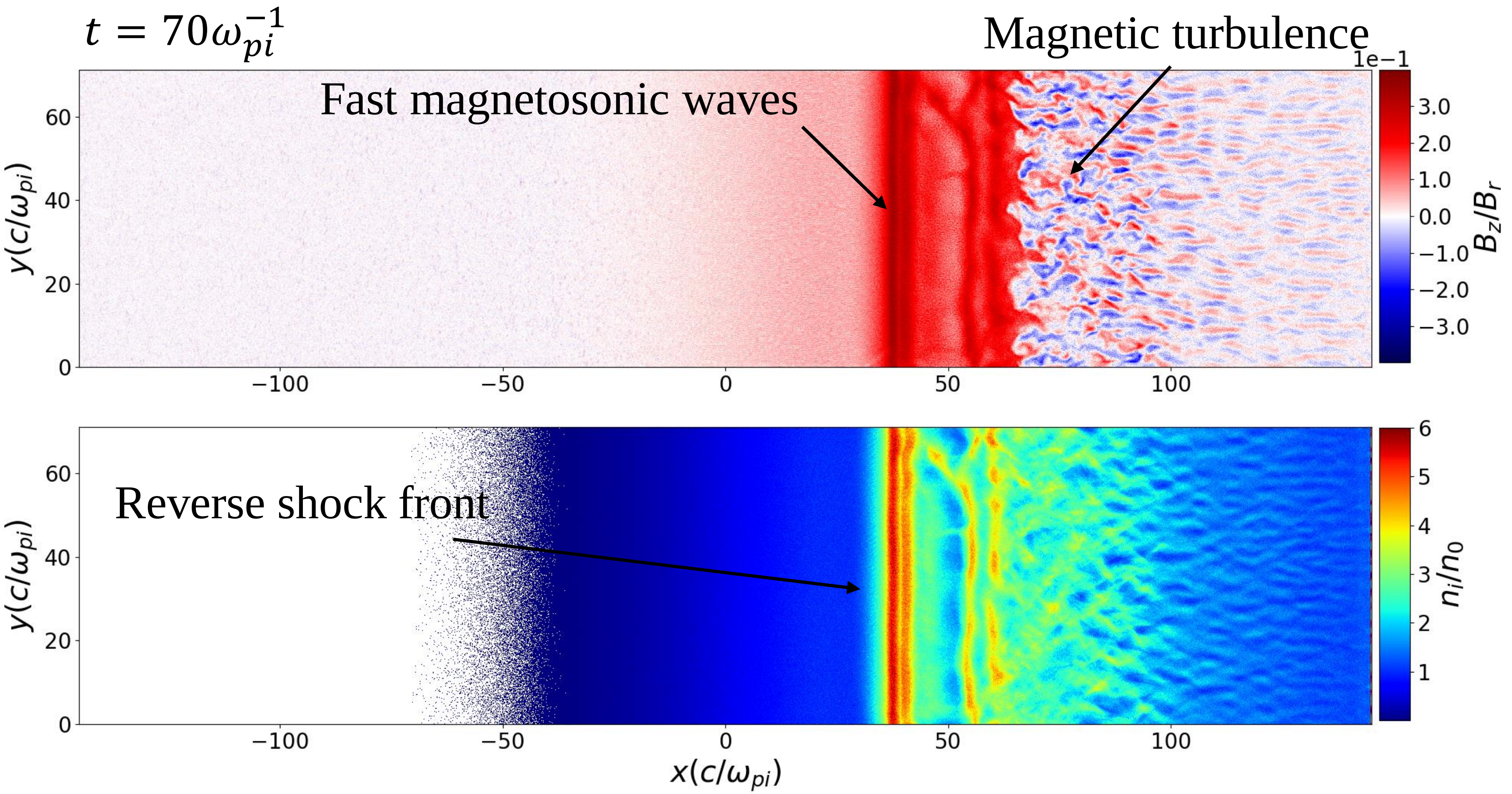
Super-Alfvenic

Supersonic
If $\mu > 1$

(Huba 2009)

Independent of μ

Shock formation ($\mu = 50$)



Shock propagation($\mu = 50$)

- Reverse shock:

$$v_r^* \simeq -\frac{3}{10} v_i \simeq c_{ms}$$

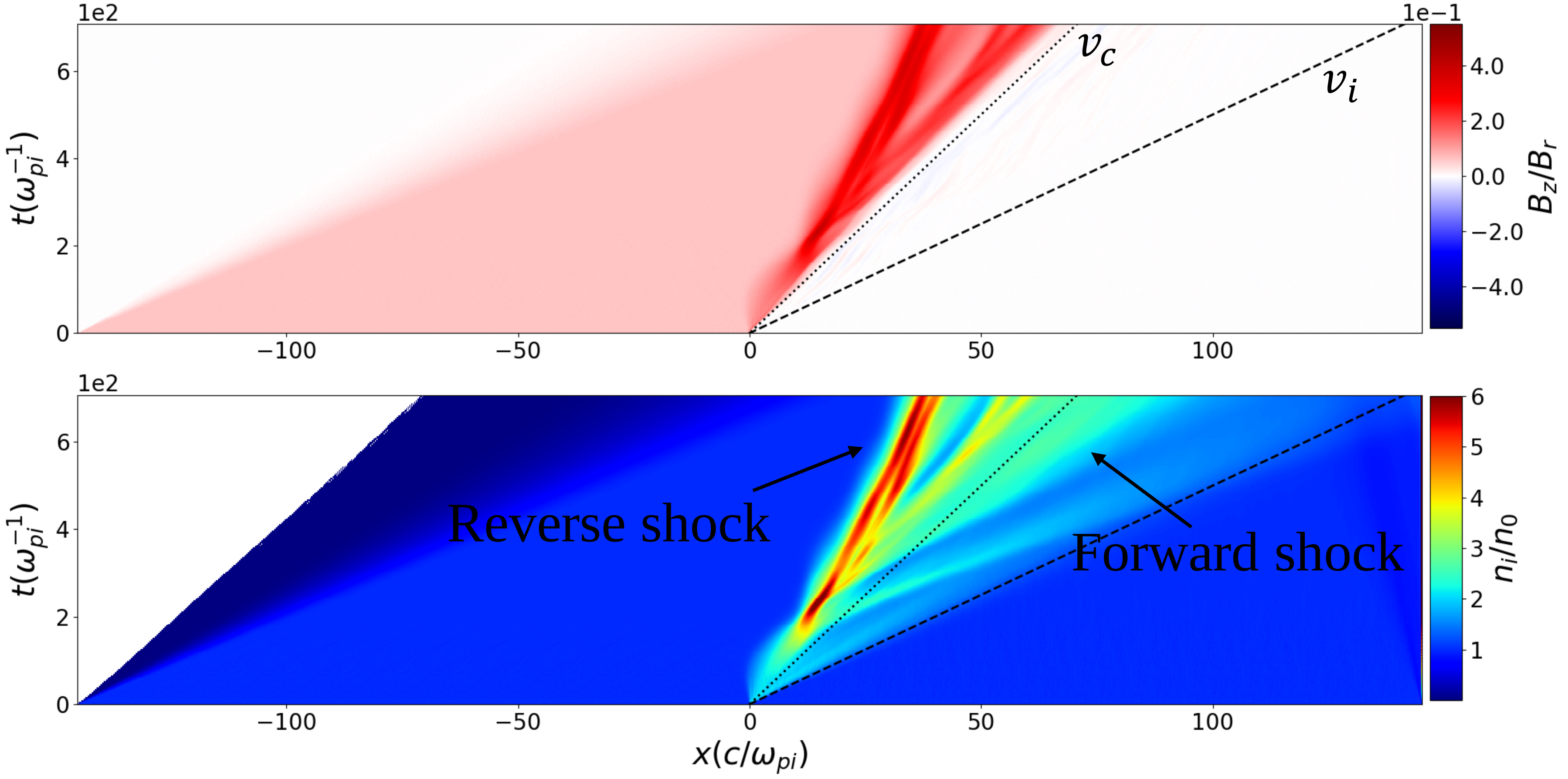
$$M_r = \frac{v_i - v_r}{c_{ms}} = 2.6\sqrt{\mu}$$

- Forward shock:

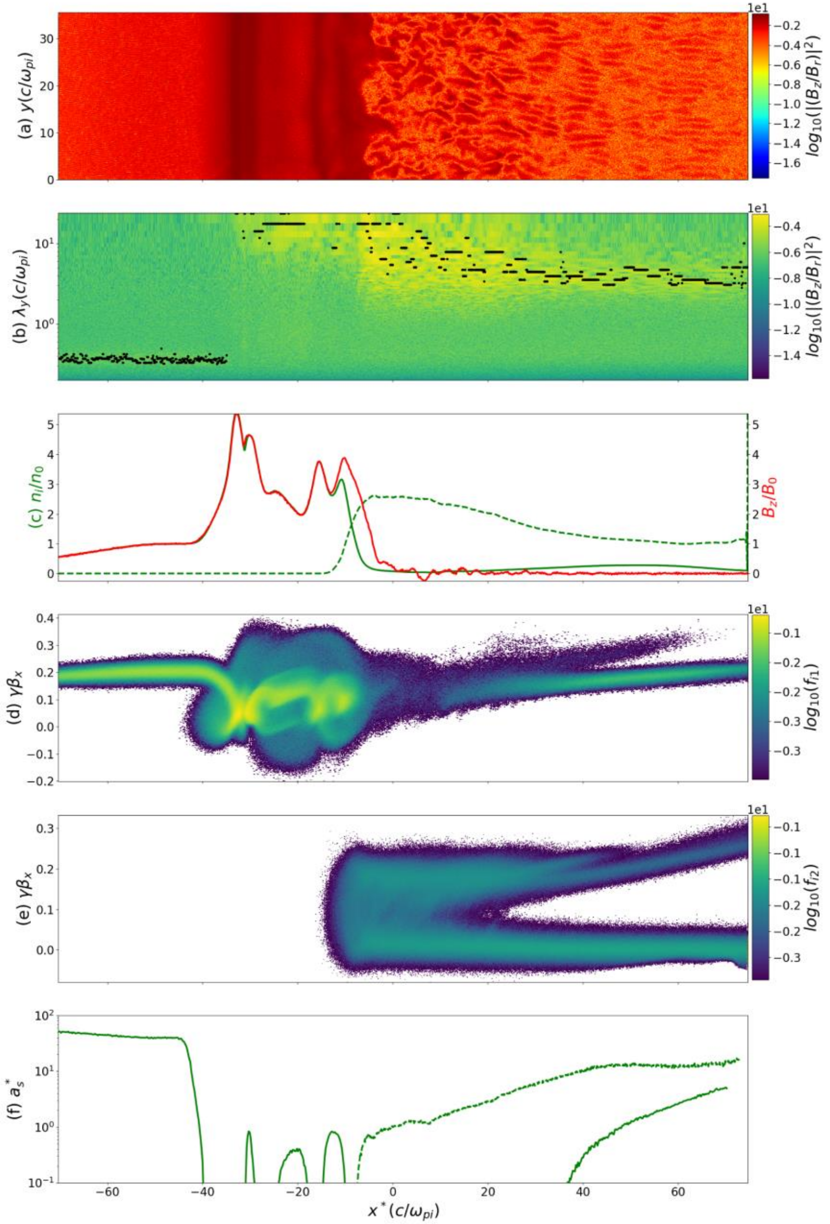
$$v_f^* \simeq \frac{1}{6} v_i \qquad M_f = \frac{v_f}{c_s} \simeq 2.2\sqrt{\mu}$$

$M_r > M_f > M_c$=1.6

Supercritical: (Marshall 1995)



Anisotropy ($\mu = 50$)

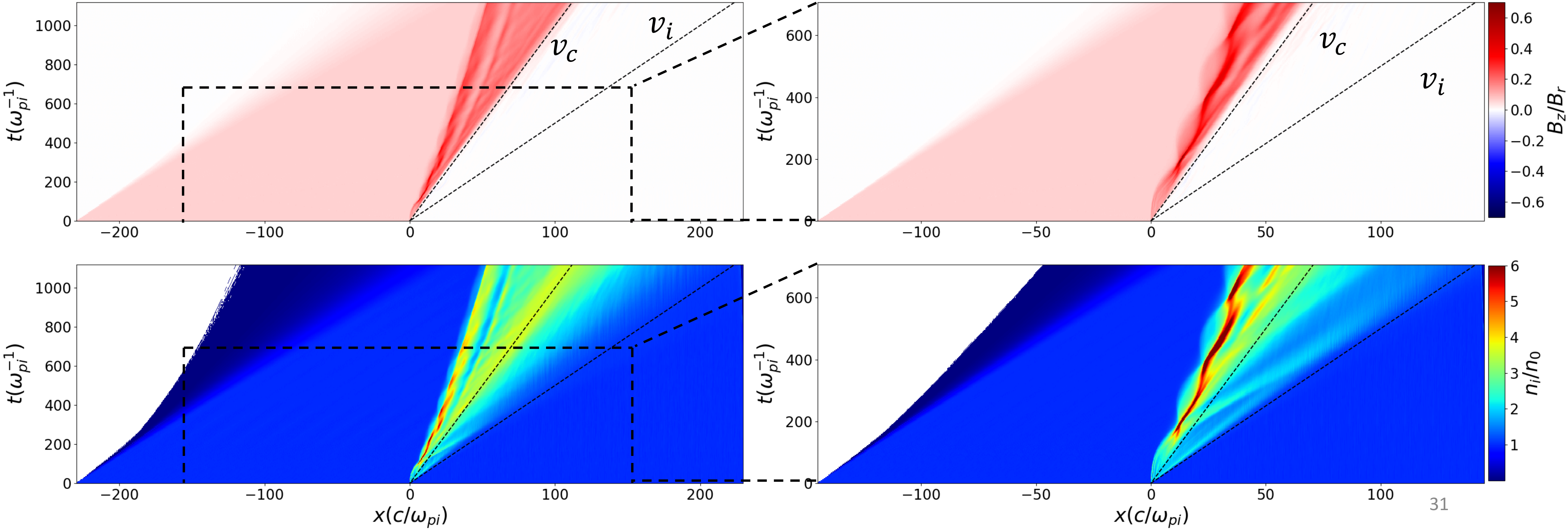


Magnetic piston: mass ratio comparaison

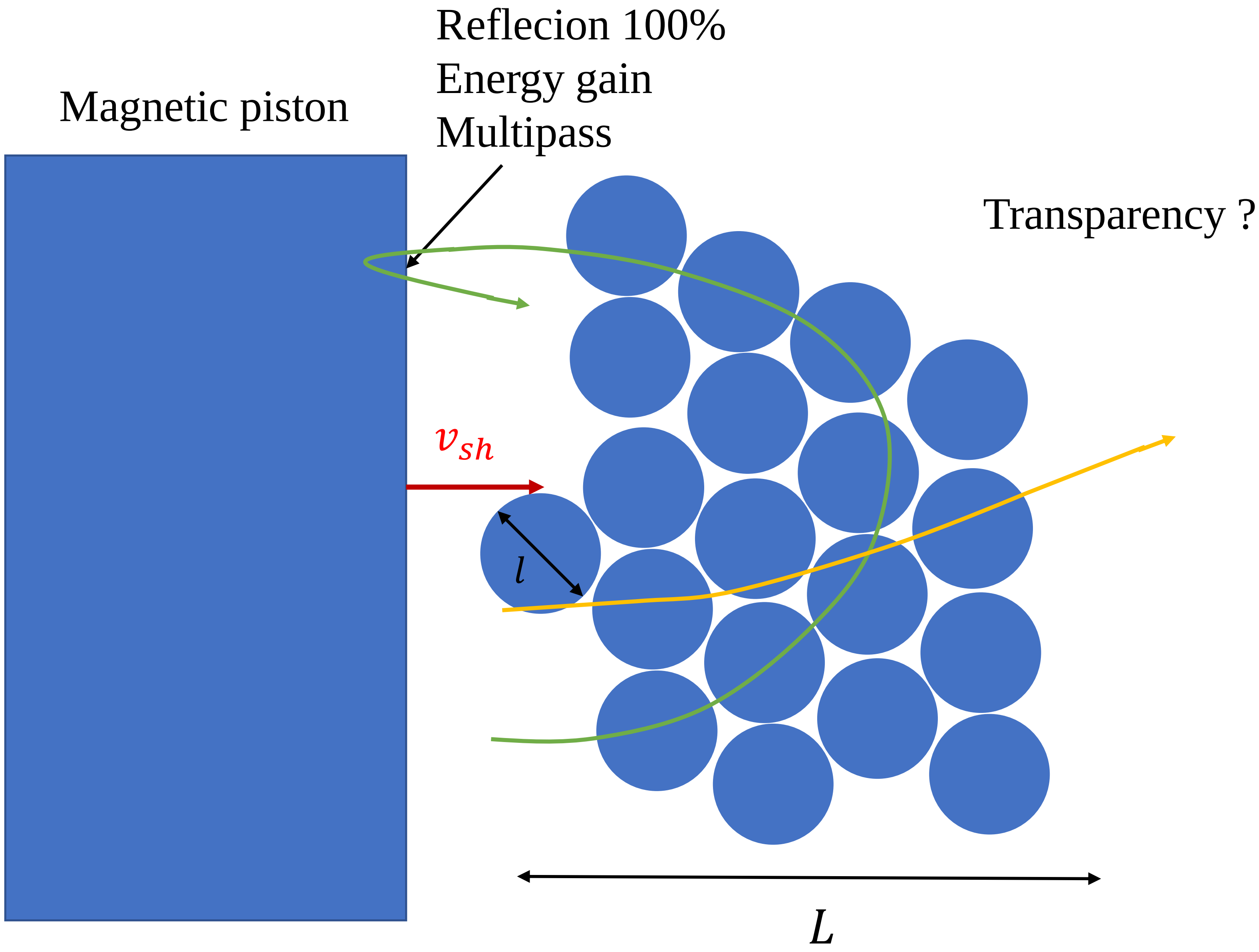
$\omega_{ci} \propto (1/\sqrt{\mu}) \times \omega_{pi}$	$\omega_{LH} \propto \omega_{pi}$
$c_s \propto (1/\sqrt{\mu})c$	$v_A \propto (1/\sqrt{\mu})c$

$$M \propto \sqrt{\mu}$$

$\mu = 20$ $\mu = 50$



Fermi acceleration: Forward shock region



Magnetic piston: Fermi I

$$\frac{\langle \Delta E \rangle}{\mathrm{E}} = \frac{4}{3}\frac{(r-1)}{r}\frac{v_{sh}}{c}$$

Upstream precurssor: Fermi II

$$\frac{\langle \Delta E \rangle}{\mathrm{E}} \propto \left(\frac{v_a}{c}\right)^2$$

Necessary for deflection and multipass, but not high energy gain